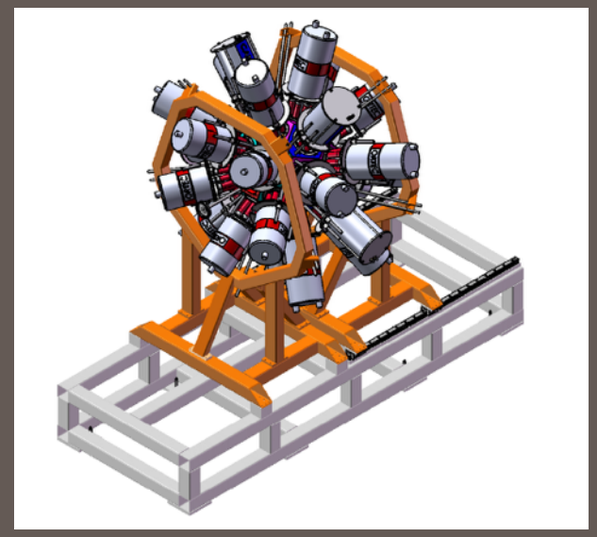
TRIUMF

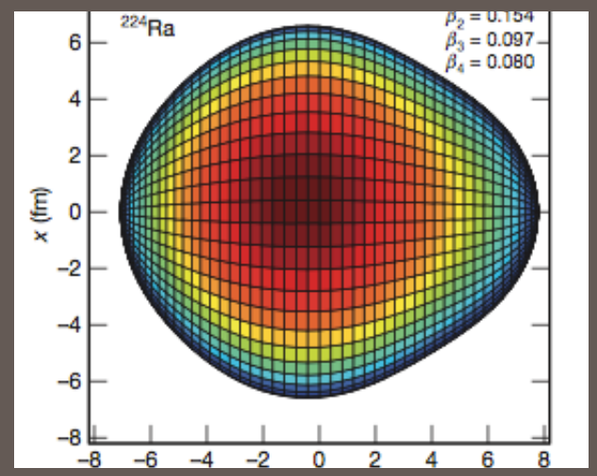
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

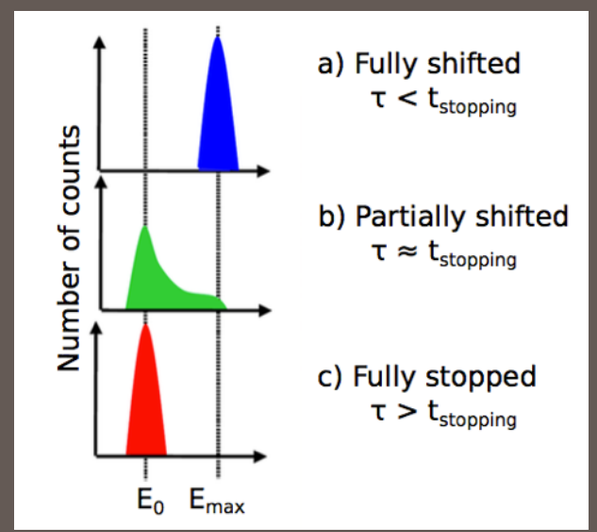
Excited-state lifetimes

TRIUMF Postdoc Lecture Series

Jack Henderson







Spectroscopy of excited states

A reminder

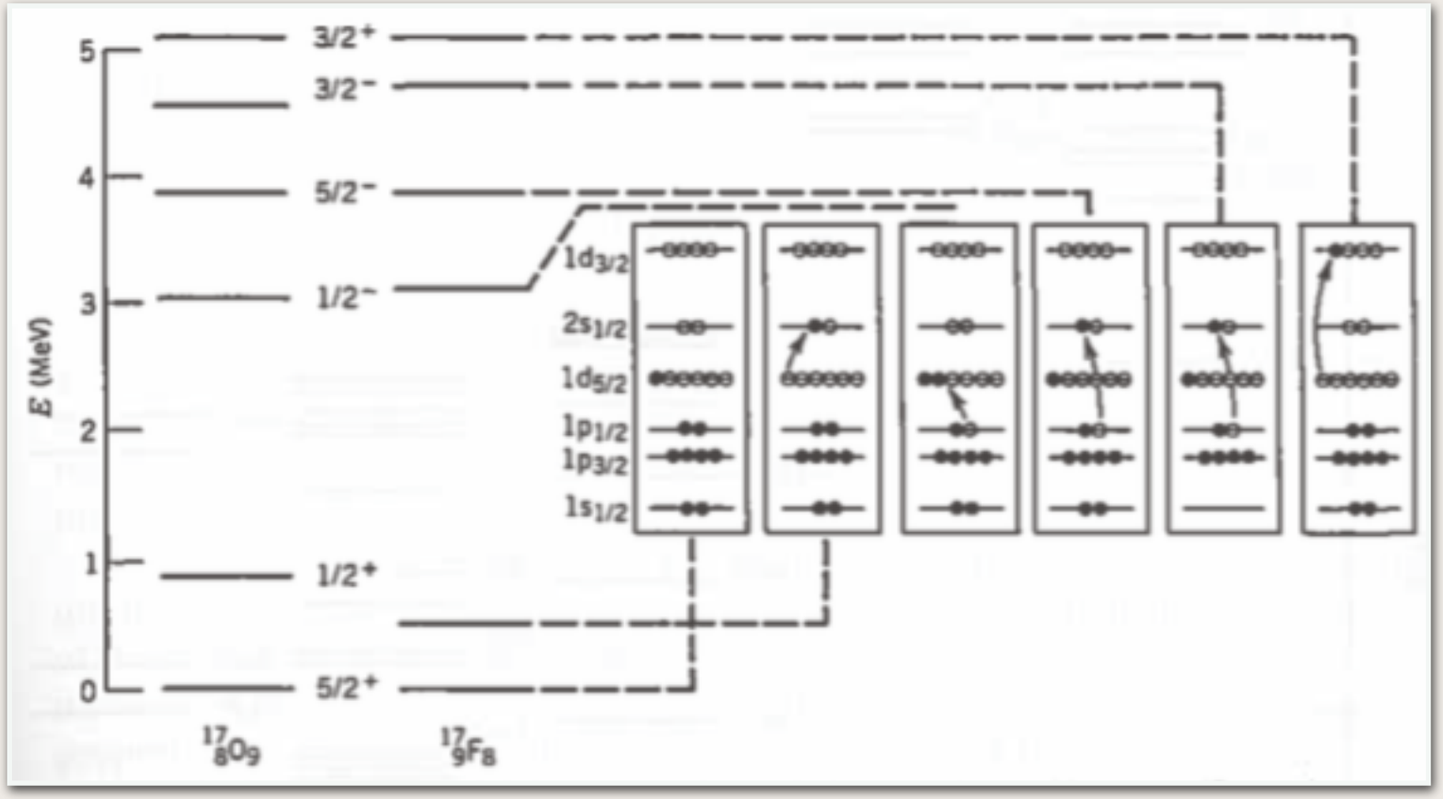
Why do we measure excited states?

How do we observe excited states?

What are the primary observables?

… why measure state lifetimes?

Why do we measure excited states?



Provide a wealth of information on the structure of the nucleus

Can identify collective and single-particle excitations of many varieties

Level spacings alone provide a lot of information

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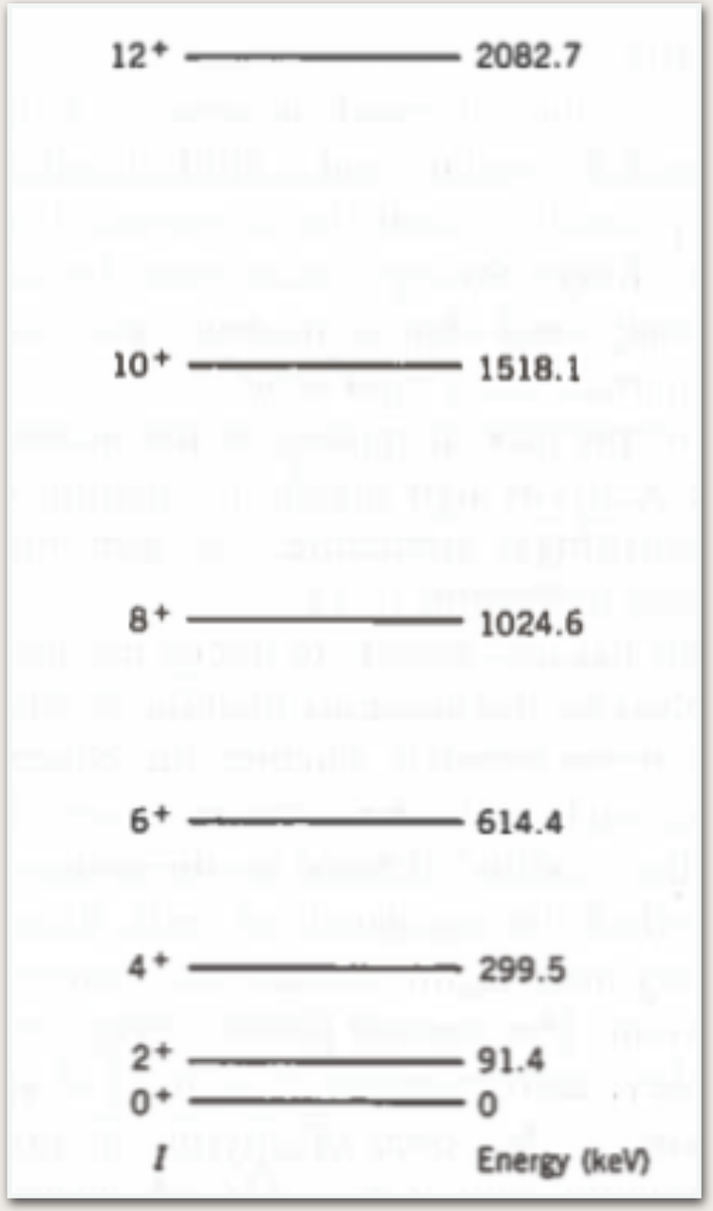


^{164}Er

$$E = \frac{\hbar^2}{2\Im} I(I+1)$$

$$E(0^+) = 0$$

$$E(2^+) = 6(\hbar^2/2\Im)$$

$$E(4^+) = 20(\hbar^2/2\Im)$$

$$E(6^+) = 43(\hbar^2/2\Im)$$

$$E(8^+) = 72(\hbar^2/2\Im)$$

^{120}Te: A lesson from history…

For many years based on its level scheme ^{120}Te was considered a textbook example of a vibrational nucleus … quite literally

Krane

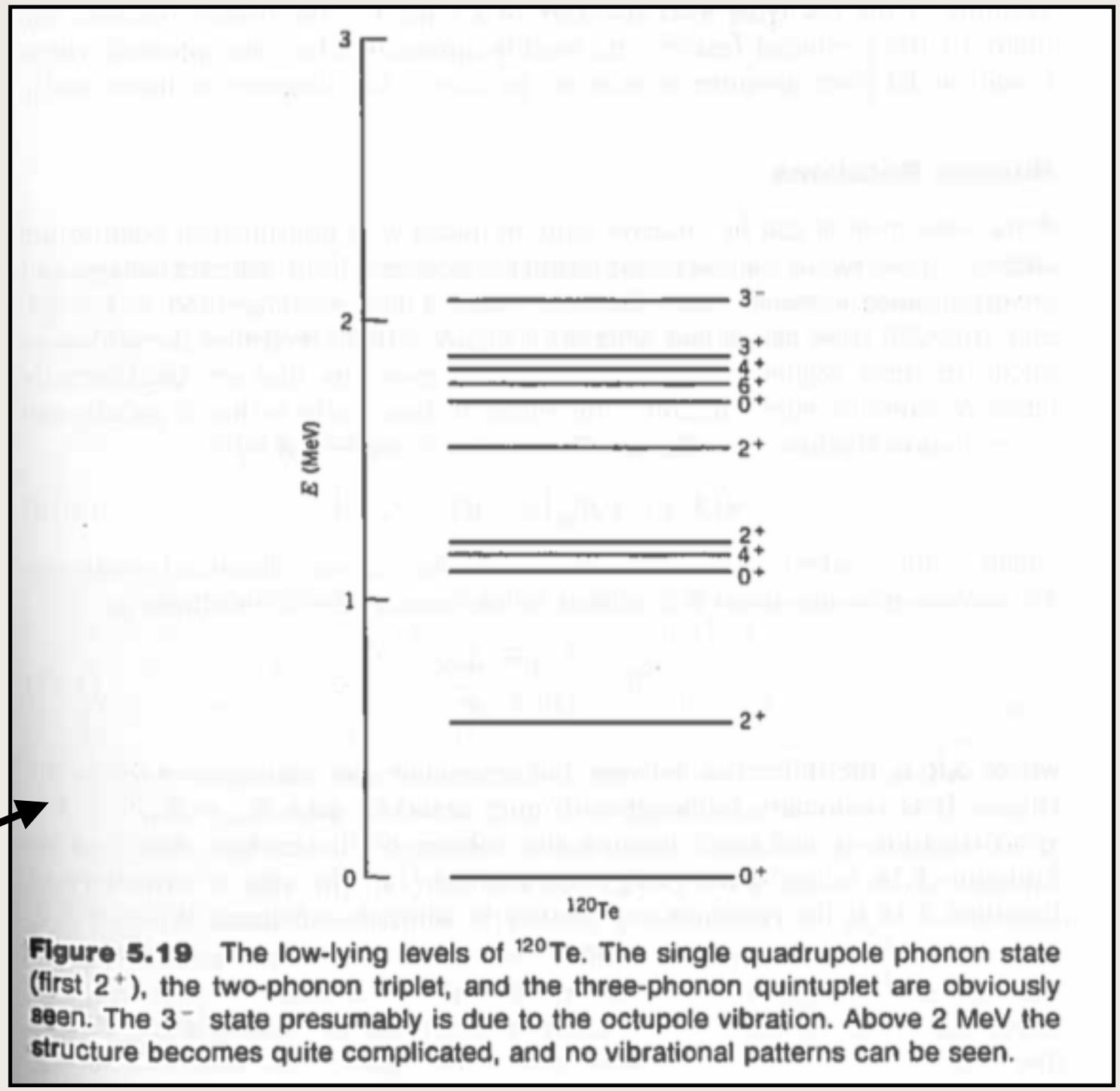


Figure 5.19 The low-lying levels of ^{120}Te. The single quadrupole phonon state (first 2^+), the two-phonon triplet, and the three-phonon quintuplet are obviously seen. The 3^- state presumably is due to the octupole vibration. Above 2 MeV the structure becomes quite complicated, and no vibrational patterns can be seen.

^{120}Te: A lesson from history…

… and then

Transition strength measurements were made

It turns out, the data fit a deformed rotor model far better than a vibrator (similarly in the Cd isotopes)

The lesson: level energies are never enough

TABLE II. Comparison of the measured data for the ^{120,122,124}Te isotopes with various available models.

	A	Experiment	Vibrator	Asymmetric rotor	IBA-2
$Q_s(2^+)/Q_0$	120		0	-0.179 $\gamma = 25°$	-0.178
$Q_s(2^+)/Q_0$	122	-0.182 (12)		-0.105 $\gamma = 27.5°$	-0.140
$Q_s(2^+)/Q_0$	124	-0.189 (16)			-0.066
$\frac{B(E2;4^+\to2^+)}{B(E2;2^+\to0^+)}$	120	1.640 (33)	2.0	1.426 $\gamma = 25°$	1.514
$\frac{B(E2;4^+\to2^+)}{B(E2;2^+\to0^+)}$	122	1.500 (40)		1.394 $\gamma = 27.5°$	1.470
$\frac{B(E2;4^+\to2^+)}{B(E2;2^+\to0^+)}$	124	1.162 (53)			1.456
$\frac{B(E2;6^+\to4^+)}{B(E2;2^+\to0^+)}$	120	2.37 (58)	3.0	1.781 $\gamma = 25°$	1.82
$\frac{B(E2;6^+\to4^+)}{B(E2;2^+\to0^+)}$	122			1.748 $\gamma = 27.5°$	1.710
$\frac{B(E2;6^+\to4^+)}{B(E2;2^+\to0^+)}$	124				1.614
$\frac{B(E2;2_2^+\to2^+)}{B(E2;2^+\to0^+)}$	120	1.215 (50)	2.0	0.906 $\gamma = 25°$	1.560
$\frac{B(E2;2_2^+\to2^+)}{B(E2;2^+\to0^+)}$	122	0.954 (74)		1.255 $\gamma = 27.5°$	1.525
$\frac{B(E2;2_2^+\to2^+)}{B(E2;2^+\to0^+)}$	124	1.115 (175)			1.540
$\frac{B(E2;2_2^+\to2^+)}{B(E2;2_2^+\to0^+)}$	120	82.9 (47)	∞	20.42 $\gamma = 25°$	105
$\frac{B(E2;2_2^+\to2^+)}{B(E2;2_2^+\to0^+)}$	122	102 (11)		82.60 $\gamma = 27.5°$	102
$\frac{B(E2;2_2^+\to2^+)}{B(E2;2_2^+\to0^+)}$	124	154 (35)			146
$B(E2;0_{g.s.}^+\to2_1^+)$	120	0.666 (20)			
$B(E2;0_{g.s.}^+\to2_1^+)$	122	0.660 (6)			
$B(E2;0_{g.s.}^+\to2_1^+)$	124	0.567 (5)			

M. Saxena et al. PRC 90 024316 (2014)

Why measure state lifetimes?

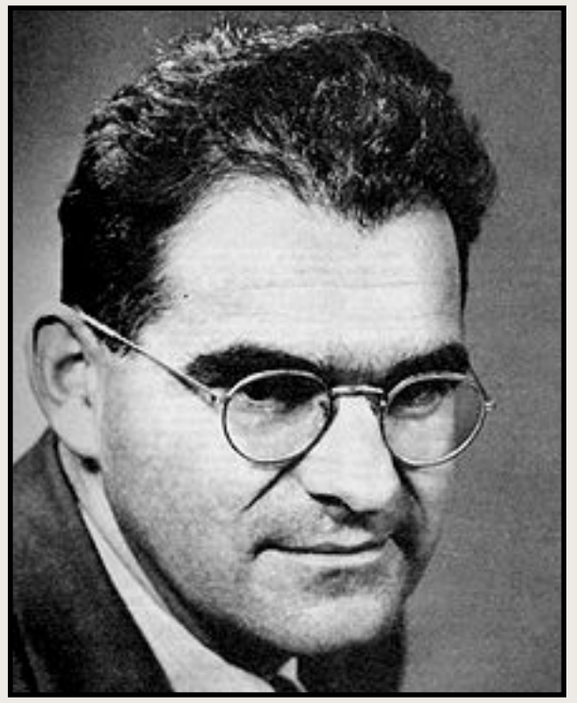
What does a state lifetime tell us?

Internal transitions are electromagnetic, and the transition probability can be defined as

$$T_{if}(\lambda L) = \frac{8\pi(L+1)}{\hbar L((2L+1)!!)^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L; J_i \to J_f)$$

Which relates the transition probability (and therefore the lifetime) to the reduced transition matrix element, B(λL)

Weisskopf estimates



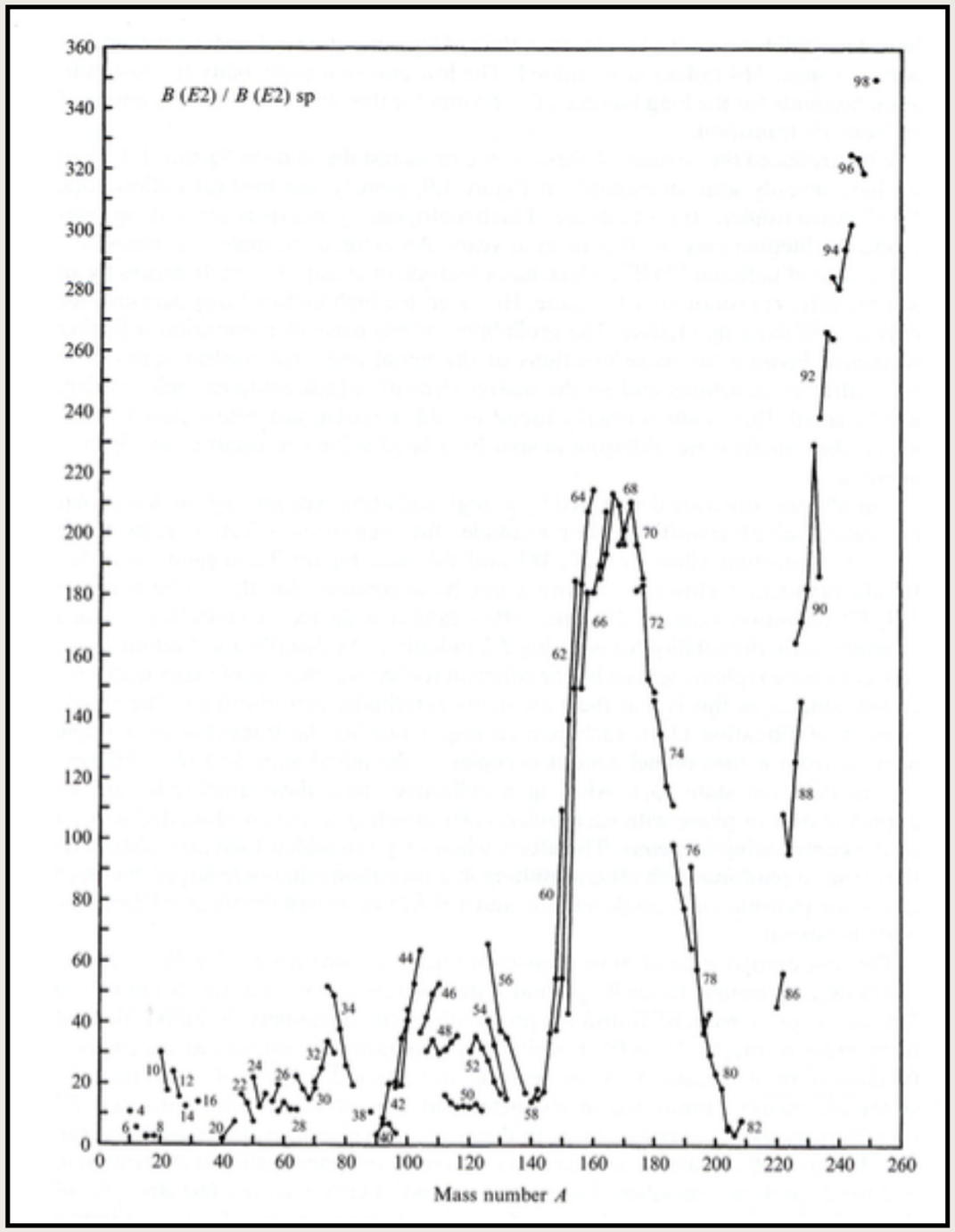
So what?

We can use this reduced matrix element to determine whether the transition is “single-particle” like

$$B(Wu:EL) = \frac{1.2^{2L}}{4\pi}\left(\frac{3}{L+3}\right)^2 A^{2L/3} e^2 fm^{2L}$$

$$B(Wu:ML) = \frac{10}{\pi} 1.2^{2L-2}\left(\frac{3}{L+3}\right)^2 A^{2L-2} 2\left(\frac{e\hbar}{2Mc}\right)^2 fm^{2L-2}$$

Again… so what?



It turns out that very few nuclear excitations can be described well by Weisskopf estimates

… need to introduce deformation and collective motion to explain this

Deformation

In the rotational model we define deformation with the intrinsic quadrupole moment, Q_0 - which we can relate to the B(E2)

$$B(E2) = \frac{5}{16\pi} Q_0^2 \left| \langle J_i K 20 | \, | J_f K \rangle \right|^2$$

… and therefore to the state lifetime

$$\frac{1}{\tau} = 1.223 E_\gamma^5 \frac{5}{16\pi} Q_0^2 \left| \langle J_i K 20 | \, | J_f K \rangle \right|^2$$

… and Q_0 is then related to the deformation parameter, β_2

$$Q_0 = \frac{3}{\sqrt{5\pi}} Z R^2 \beta_2 \left(1 + \frac{1}{8} \sqrt{\frac{5}{\pi}} \beta_2 + ... \right)$$

Single-particle structure

On the other hand, M1 transitions relate closely to the single particle structure of a nucleus

Under certain conditions, for example:

$$B(M1) = \frac{3}{4\pi}\mu_N^2(g_R - g_R)^2K^2\frac{(I-K)(I+K)}{I(2I+1)}$$

g_K and g_R are the single particle and collective g factors, which relate to the magnetic moment - itself related to the nucleon configuration

K is the projection of the band on the symmetry axis

Lifetime measurement regimes

- A number of experimental techniques are available
- Each is suited to a different regime (with some overlap)
- Techniques cover practically all potential lifetimes… with provisos

	Lower limit	Upper limit
Electronic timing	10 ps	∞*
RDDS	1 ps	100 ps
DSAM	10 fs	10 ps
Lineshape	1 fs	100 fs
CouEx	0*	∞*

* with some provisos

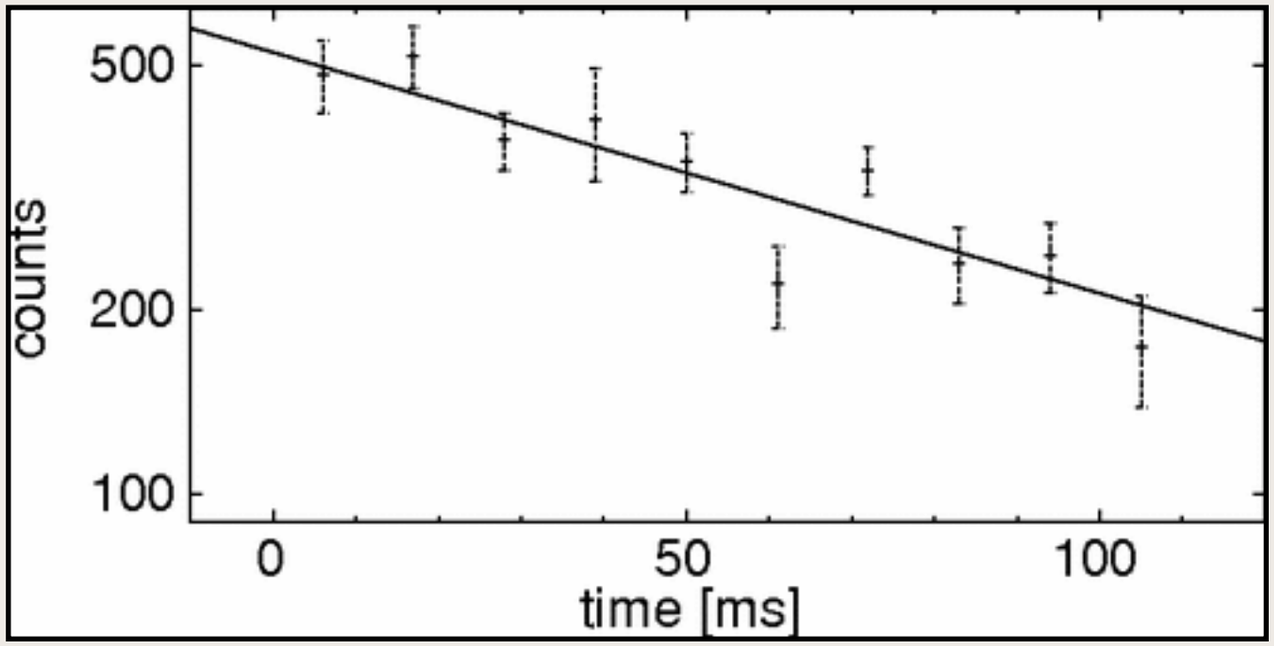
“Long-lived” states

We’ll define these as anything longer lived than ~1-10 ns (depending on stats)

No specialized experimental equipment required

… basically, isomers

$$N(t) = N_0 e^{(-\frac{t}{\tau})}$$



J. Kurpeta et al., PRC 82 064318 (2010)

“Long-lived” states

An example:

^{130}Xe	^{131}Xe	^{132}Xe	^{133}Xe	^{134}Xe	^{135}Xe	^{136}Xe	^{137}Xe	^{138}Xe	^{139}Xe	^{140}Xe	^{141}Xe	^{142}Xe	^{143}Xe	^{144}Xe	^{145}Xe	^{146}Xe	^{147}Xe	^{148}Xe
^{129}I	^{130}I	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{136}I	^{137}I	^{138}I	^{139}I	^{140}I	^{141}I	^{142}I	^{143}I	^{144}I	^{145}I	Iodine Z=53	
^{128}Te	^{129}Te	^{130}Te	^{131}Te	^{132}Te	^{133}Te	^{134}Te	^{135}Te	^{136}Te	^{137}Te	^{138}Te	^{139}Te	^{140}Te	^{141}Te	^{142}Te	^{143}Te	Tellurium Z=52		
^{127}Sb	^{128}Sb	^{129}Sb	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb	^{135}Sb	^{136}Sb	^{137}Sb	^{138}Sb	^{139}Sb	^{140}Sb	Antimony Z=51				
^{126}Sn	^{127}Sn	^{128}Sn	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn	^{134}Sn	^{135}Sn	^{136}Sn	^{137}Sn	^{138}Sn	Tin Z=50					
^{125}In	^{126}In	^{127}In	^{128}In	^{129}In	^{130}In	^{131}In	^{132}In	^{133}In	^{134}In	^{135}In	Indium Z=49							
^{124}Cd	^{125}Cd	^{126}Cd	^{127}Cd	^{128}Cd	^{129}Cd	^{130}Cd	^{131}Cd	^{132}Cd	^{133}Cd	Cadmium Z=48								
^{123}Ag	^{124}Ag	^{125}Ag	^{126}Ag	^{127}Ag	^{128}Ag	^{129}Ag	^{130}Ag	Silver Z=47										
^{122}Pd	^{123}Pd	^{124}Pd	^{125}Pd	^{126}Pd	^{127}Pd	^{128}Pd	Palladium Z=46											

“Seniority” isomers

Sn seniority isomers

In the vicinity of closed shells low-lying excited states are constructed by breaking pairs.

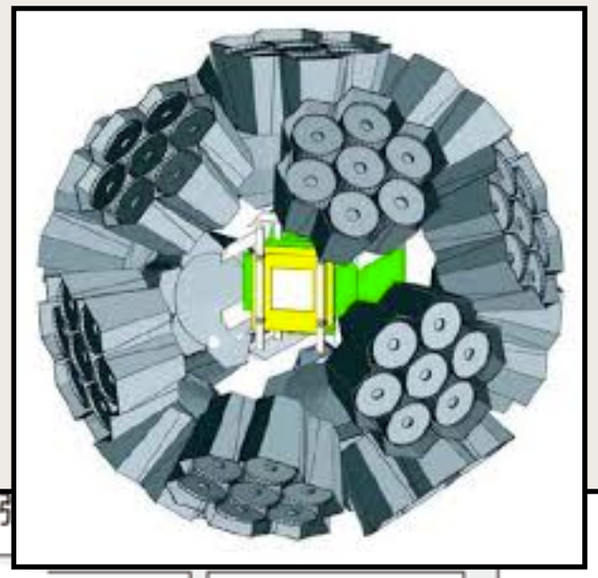
^{130}Xe	^{131}Xe	^{132}Xe	^{133}Xe	^{134}Xe	^{135}Xe	^{136}Xe	^{137}Xe	^{138}Xe	^{139}Xe	^{140}Xe	^{141}Xe	^{142}Xe	^{143}Xe	^{144}Xe	^{145}Xe	^{146}Xe	^{147}Xe	^{148}Xe
^{129}I	^{130}I	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{136}I	^{137}I	^{138}I	^{139}I	^{140}I	^{141}I	^{142}I	^{143}I	^{144}I	^{145}I	Iodine Z=53	
^{128}Te	^{129}Te	^{130}Te	^{131}Te	^{132}Te	^{133}Te	^{134}Te	^{135}Te	^{136}Te	^{137}Te	^{138}Te	^{139}Te	^{140}Te	^{141}Te	^{142}Te	^{143}Te	Tellurium Z=52		
^{127}Sb	^{128}Sb	^{129}Sb	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb	^{135}Sb	^{136}Sb	^{137}Sb	^{138}Sb	^{139}Sb	^{140}Sb	Antimony Z=51				
^{126}Sn	^{127}Sn	^{128}Sn	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn	^{134}Sn	^{135}Sn	^{136}Sn	^{137}Sn	^{138}Sn	Tin Z=50					
^{125}In	^{126}In	^{127}In	^{128}In	^{129}In	^{130}In	^{131}In	^{132}In	^{133}In	^{134}In	^{135}In	Indium Z=49							
^{124}Cd	^{125}Cd	^{126}Cd	^{127}Cd	^{128}Cd	^{129}Cd	^{130}Cd	^{131}Cd	^{132}Cd	^{133}Cd	Cadmium Z=48								
^{123}Ag	^{124}Ag	^{125}Ag	^{126}Ag	^{127}Ag	^{128}Ag	^{129}Ag	^{130}Ag	Silver Z=47										
^{122}Pd	^{123}Pd	^{124}Pd	^{125}Pd	^{126}Pd	^{127}Pd	^{128}Pd	Palladium Z=46											

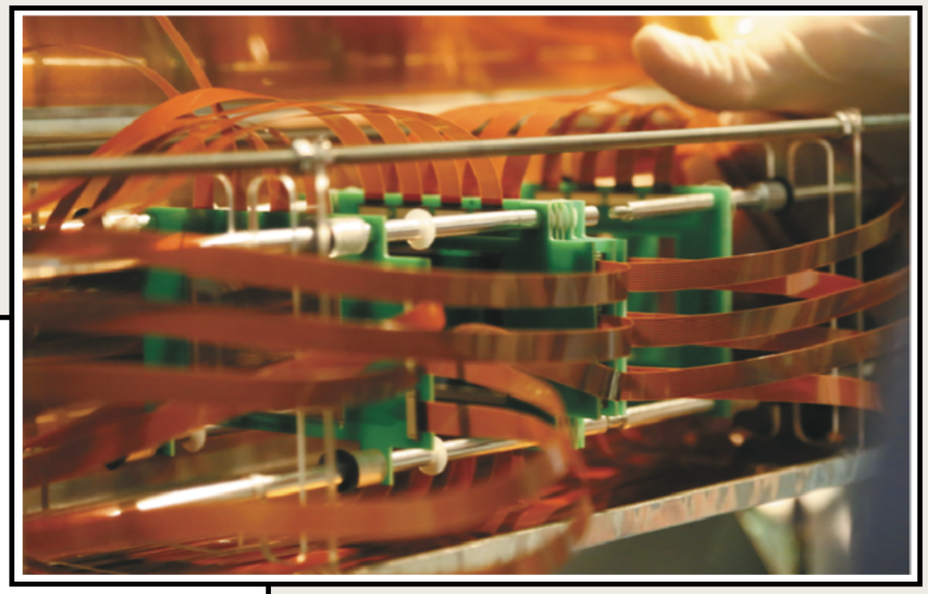
Experiment looking for these isomers in ^{136,138}Sn performed at RIBF - RIKEN (Japan)

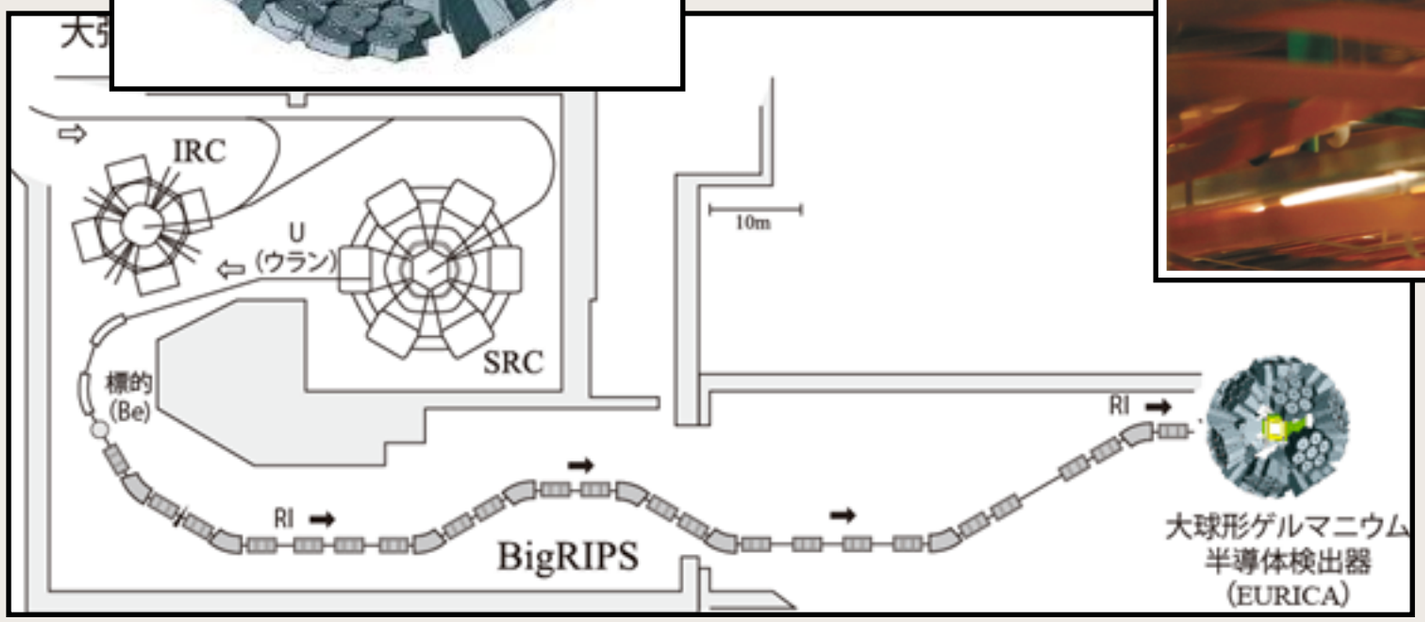
Results in isomerism.
See lecture 6 - shell evolution

Sn seniority isomers

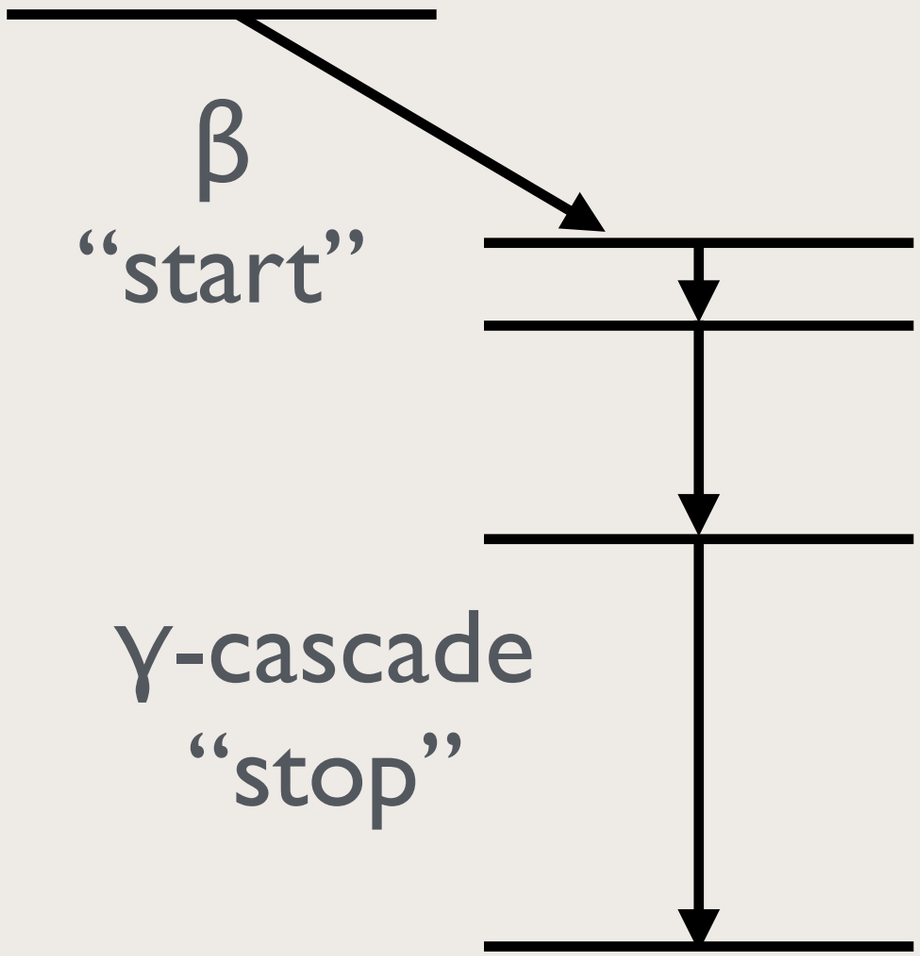
Beta-delayed gamma spectroscopy (see e.g. GRIFFIN)



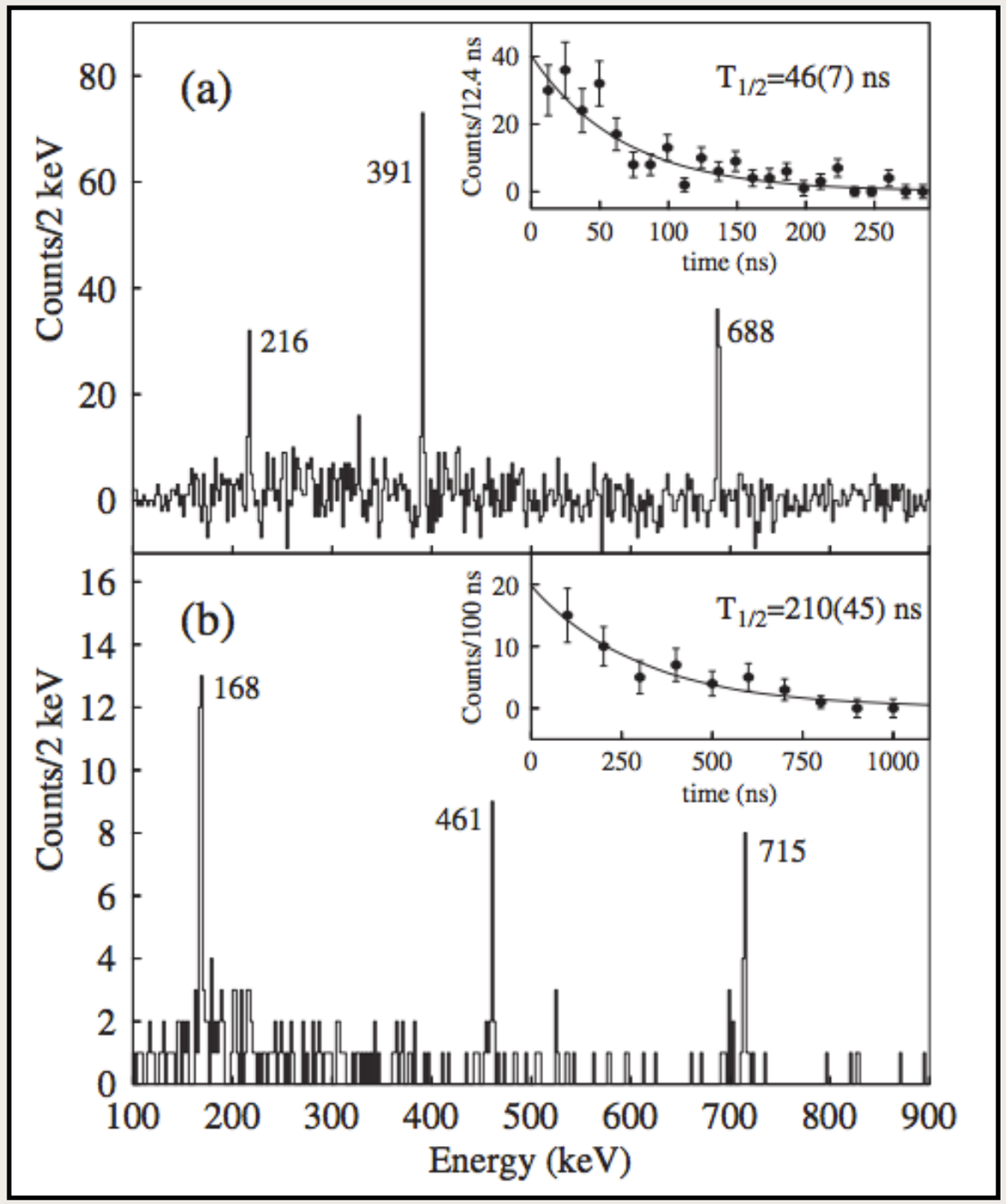




Sn seniority isomers



Cascade "prompt" with isomer



Fast electronic timing

- Specialized setup using fast response detectors
- HPGe and Si detectors no-longer fit the bill
- Need something… faster

	$LaBr_3$	NaI(Tl)	BaF_2	BGO
Light Yield LY [ph./keV]	61	41	1.8	9
Decay Time τ [ns]	16	250	0.7	300
F.O.M (τ/LY)	0.26	6	0.38	33
Energy Res. @662 keV	2.7	5.6	11.4	9

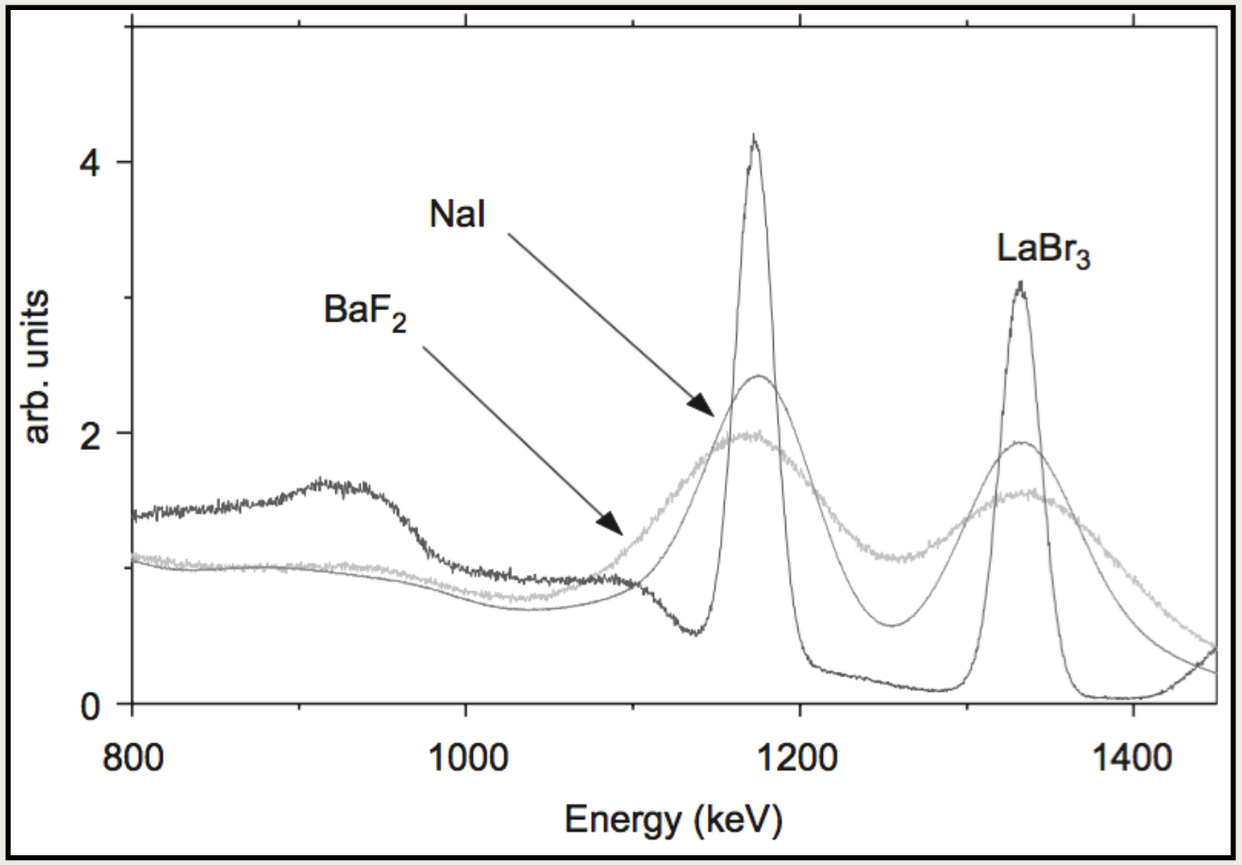
$LaBr_3$(Ce) fits the bill

Why $LaBr_3$?

Aside from the obviously beneficial fast rise-time…

Large light-yield / MeV

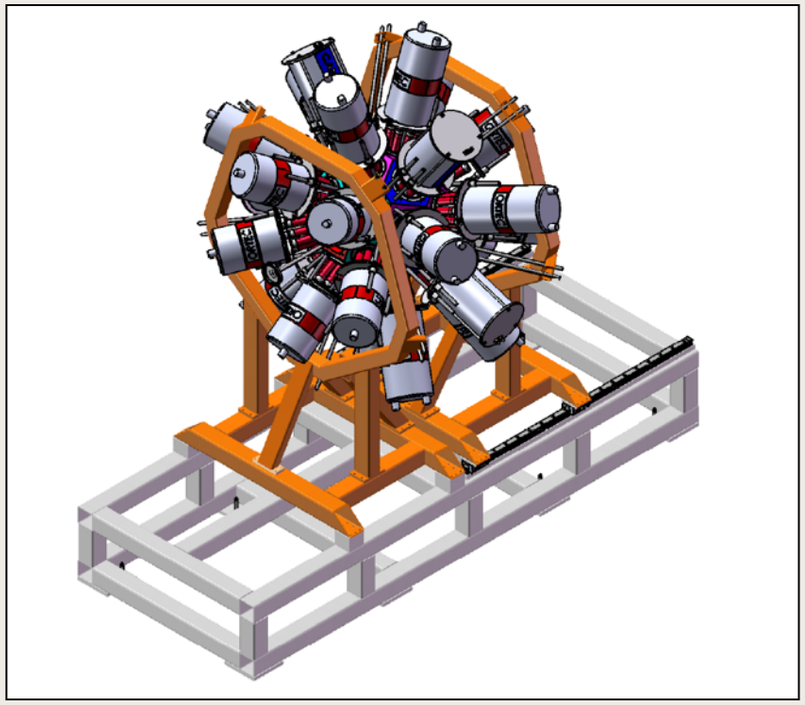
Makes selecting the transition of interest more practical

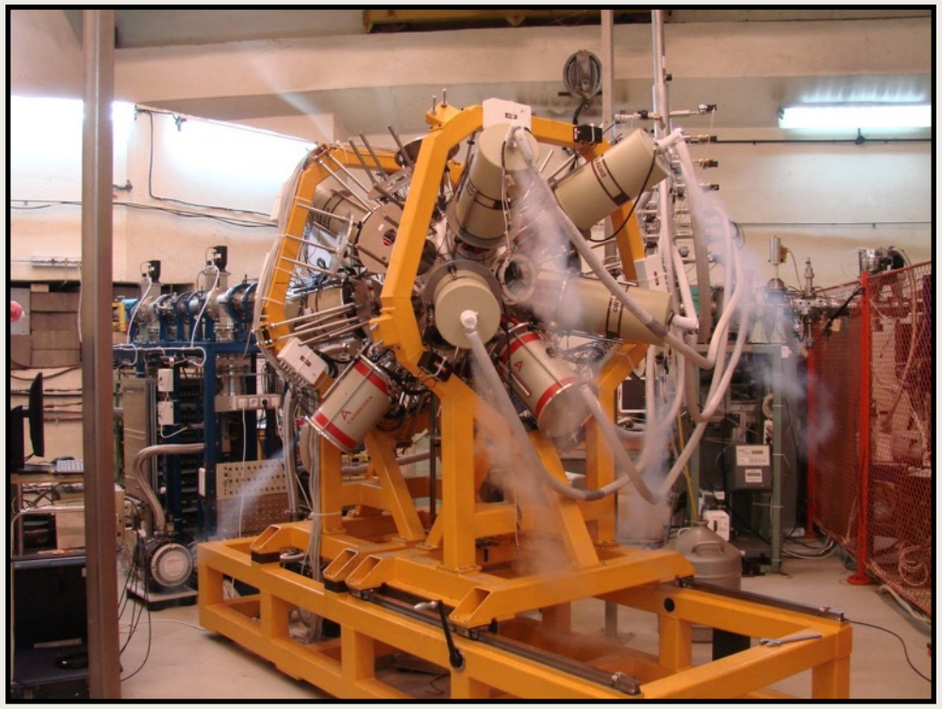


Large signal also means less "jitter" in the timing signal

Fast timing systems

There are now a few dedicated fast-timing setups around the world - typically coupled with HPGe

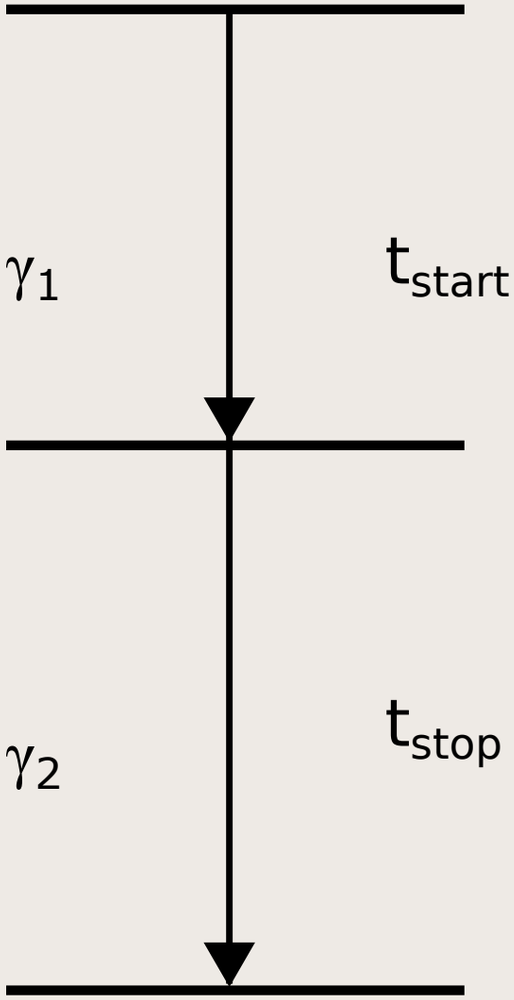


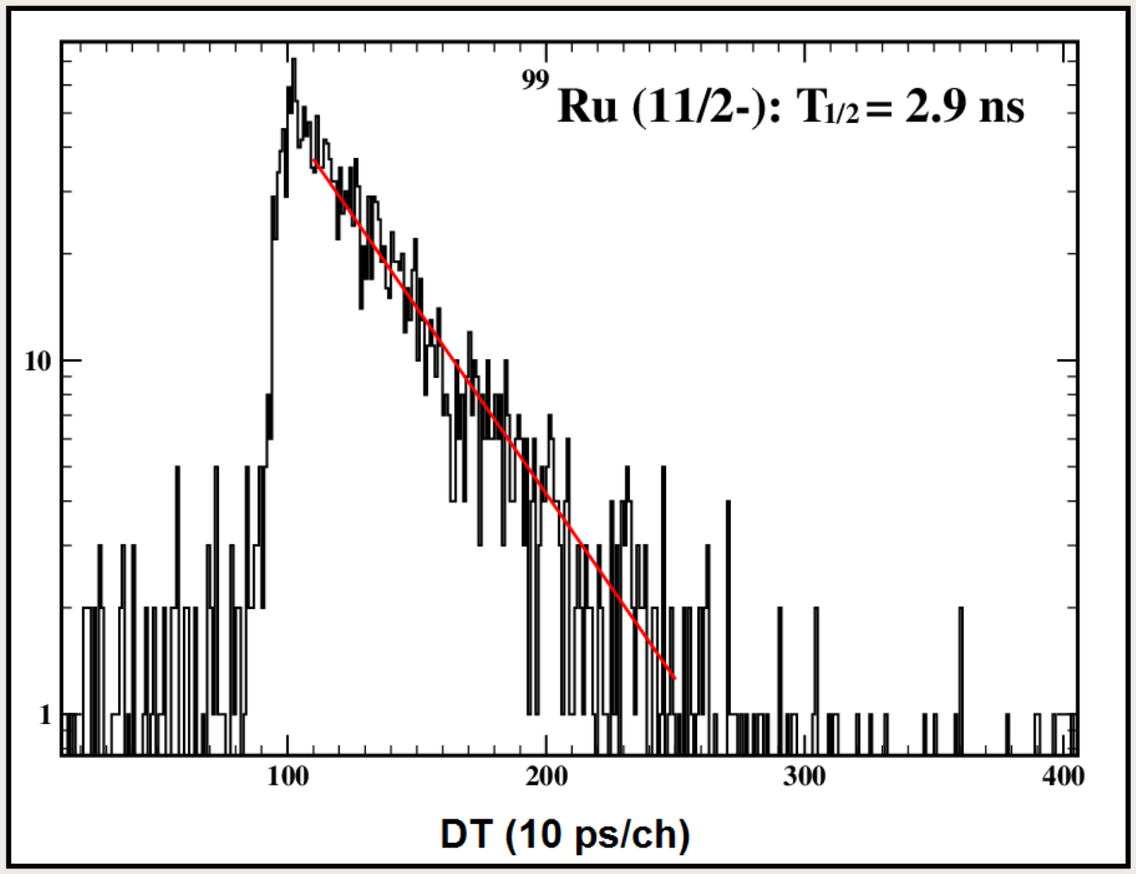


Also regularly folded into other spectroscopy setups (GRIFFIN, EURICA, etc.)

Fast electronic timing

Gate on feeding transition (start)





Gate on decay transition (stop)

Feeding

In direct lifetime measurements feeding isn't really an issue

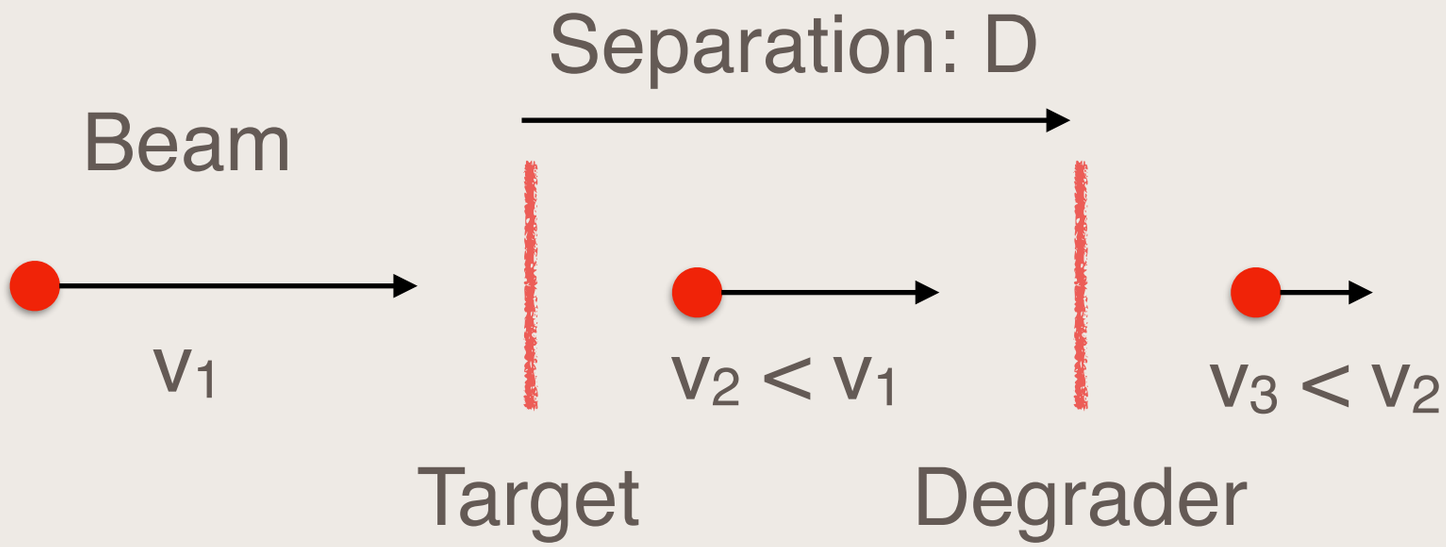
Becomes important when you cannot explicitly gate on the transition into a state

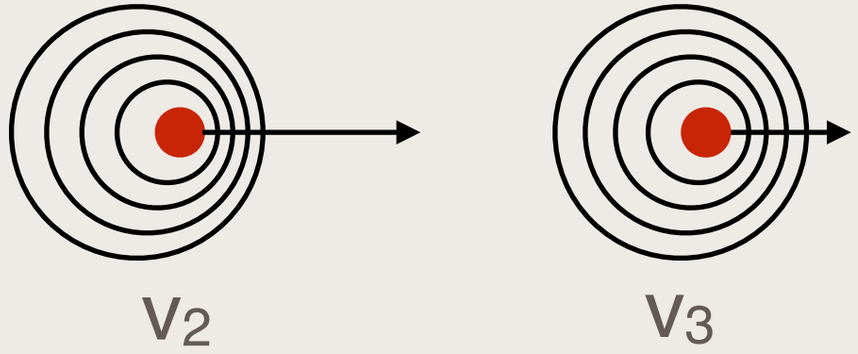
Can sometimes be neglected for vastly different lifetimes

Generally an issue which plagues lifetime measurements - in particular older ones

As a rule: if the data weren't taken with some form of coincidences, there's a good chance they're wrong…

Recoil-distance Doppler shift

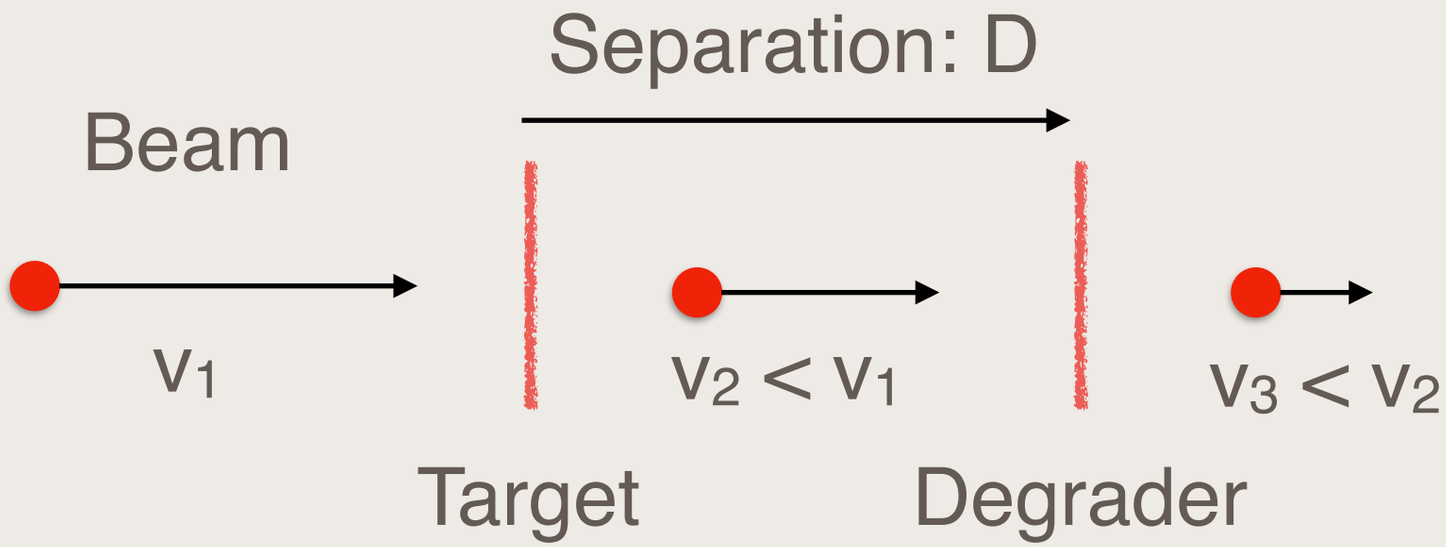


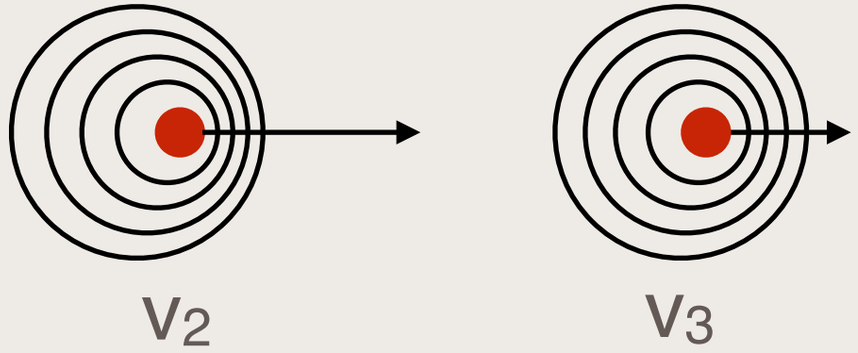


Lifetimes sufficiently short that we can't directly measure them

Use some physical effects to help us

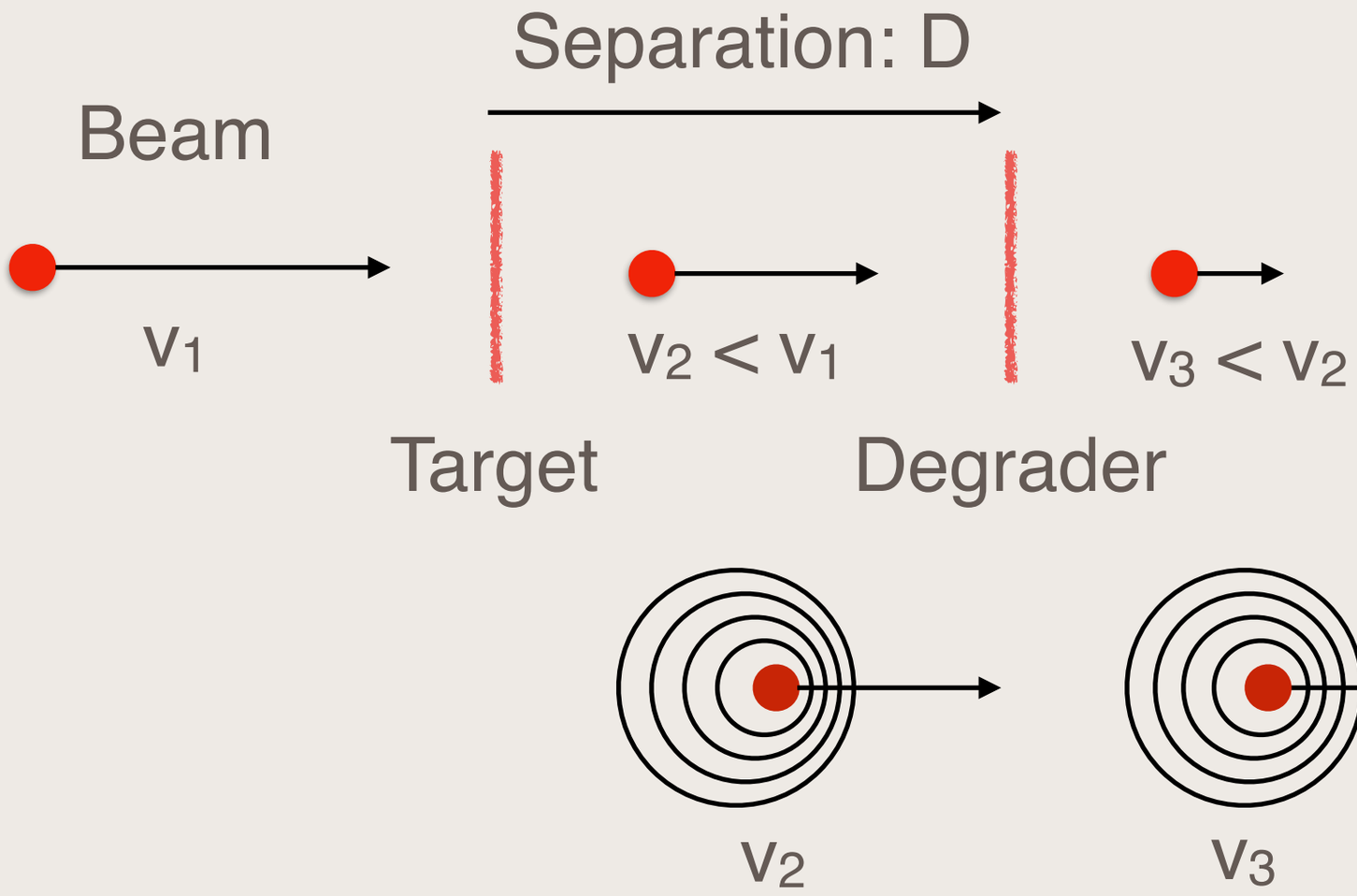
Recoil-distance Doppler shift





$$E'_\gamma = \frac{E_\gamma}{\gamma \cdot (1 - \beta cos(\theta))}$$

Recoil-distance Doppler shift



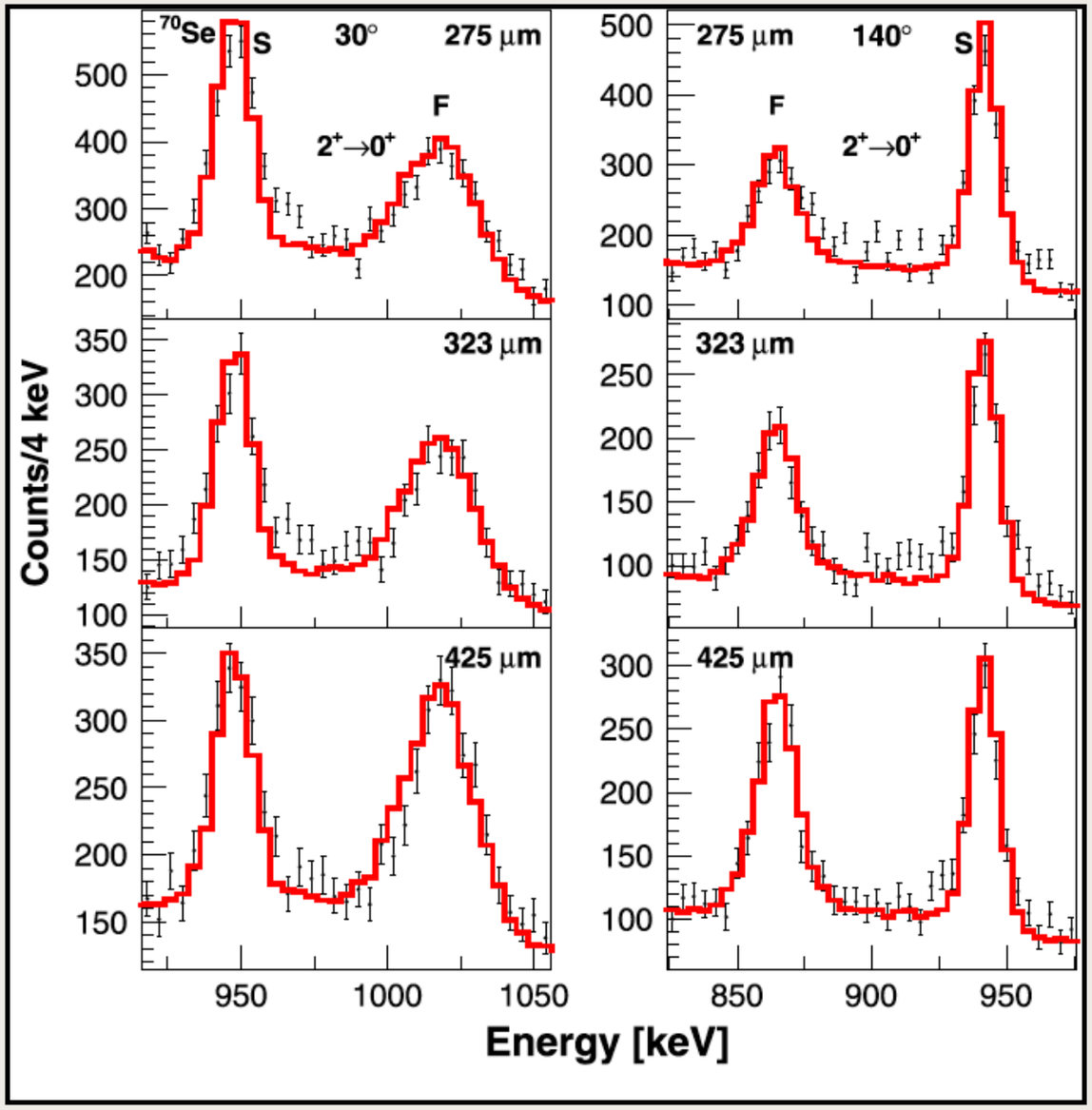
Run at multiple separation distances to effectively probe different times

Recoil-distance Doppler shift

Example spectra taken at NSCL (Michigan)

Left hand spectra are forward angles (“blue shifted”), right hand backwards (“red shifted”)

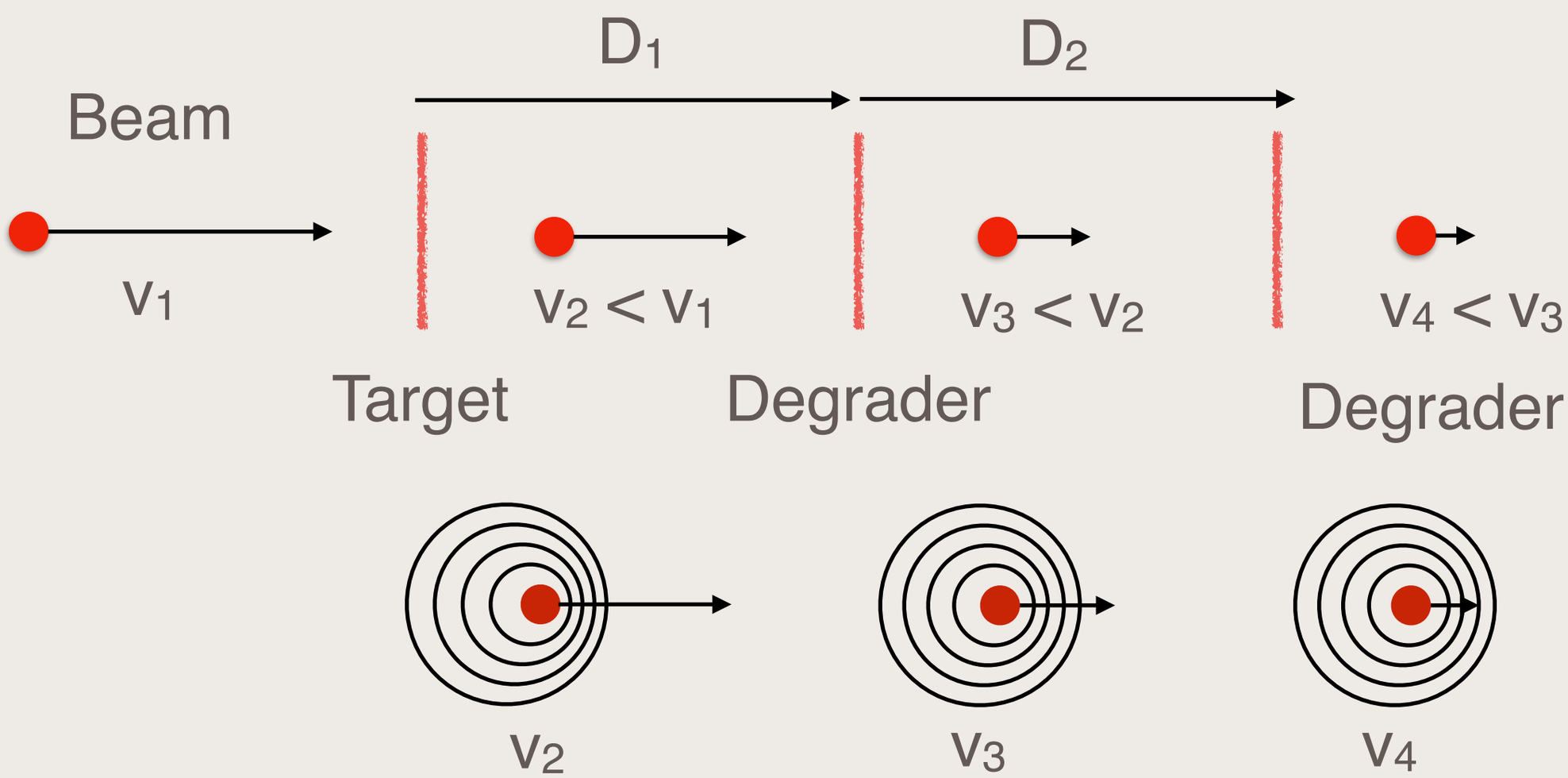
We see the ratio of components in the slow (S) and fast (F) peaks changes as we move the plunger



A. J. Nichols et al., Phys. Lett. B **733** 52 (2014)

Recoil-distance Doppler shift

Alternatively: a triple plunger

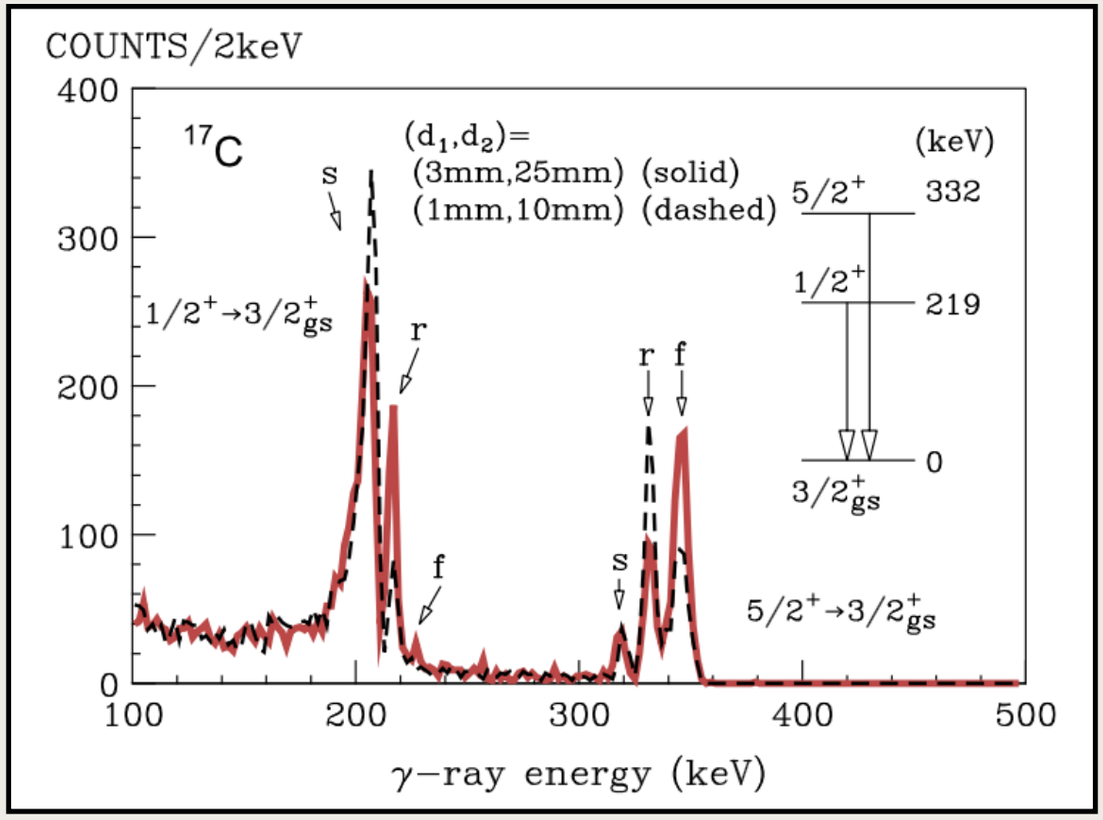


Recoil-distance Doppler shift

$$\tau \approx \frac{\Delta x}{v} \frac{I^s}{I^r}$$

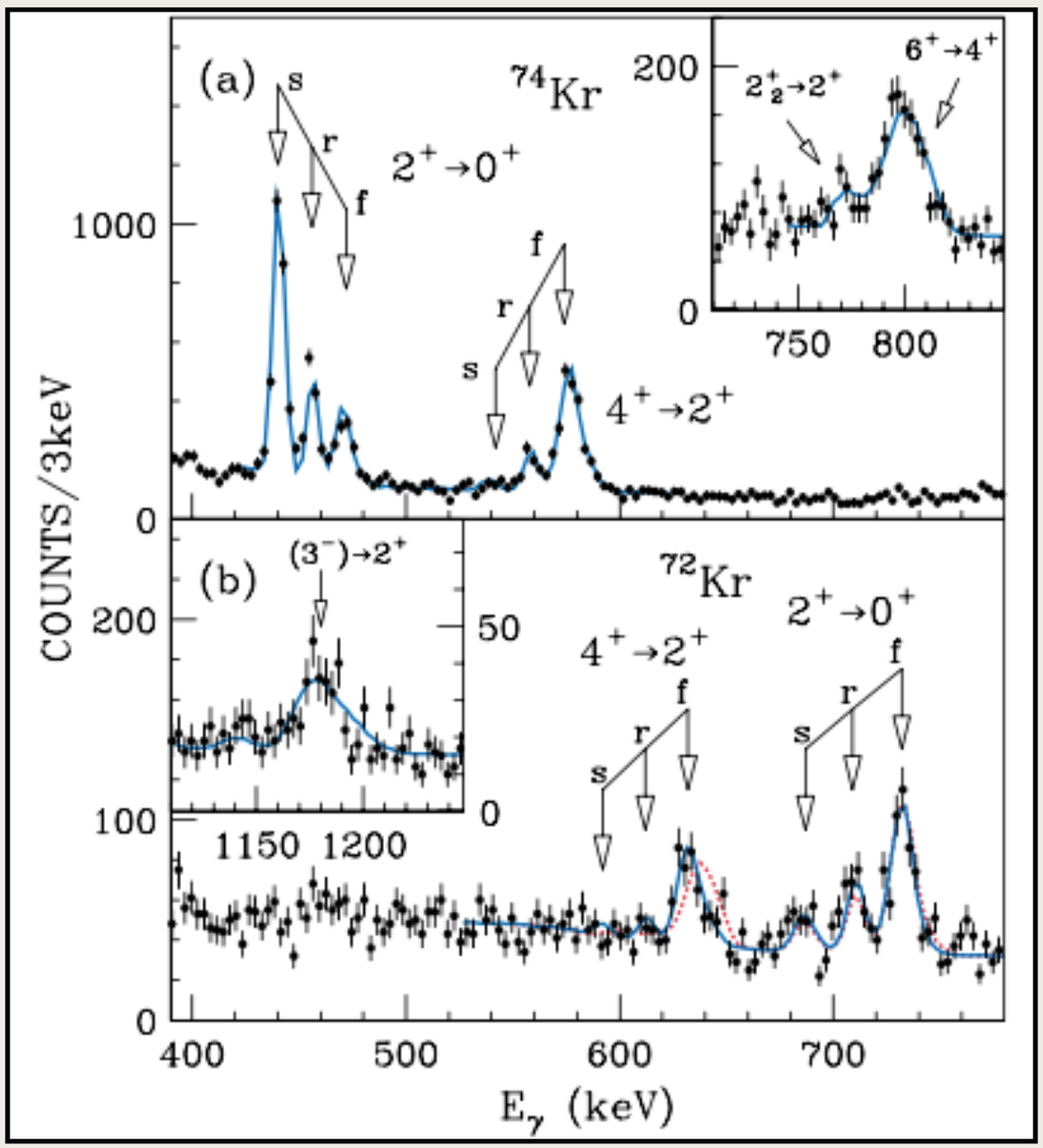
Three foils - means you can probe two decay lifetimes simultaneously

e.g. 17C: $\tau(1/2^+) \approx 500$ ps, $\tau(5/2^+) \approx 20$ ps



Recoil-distance Doppler shift

Example, ^{72}Kr:



Oblate ground state, first-excited 0^+ state, potential transition to prolate at low excitation E

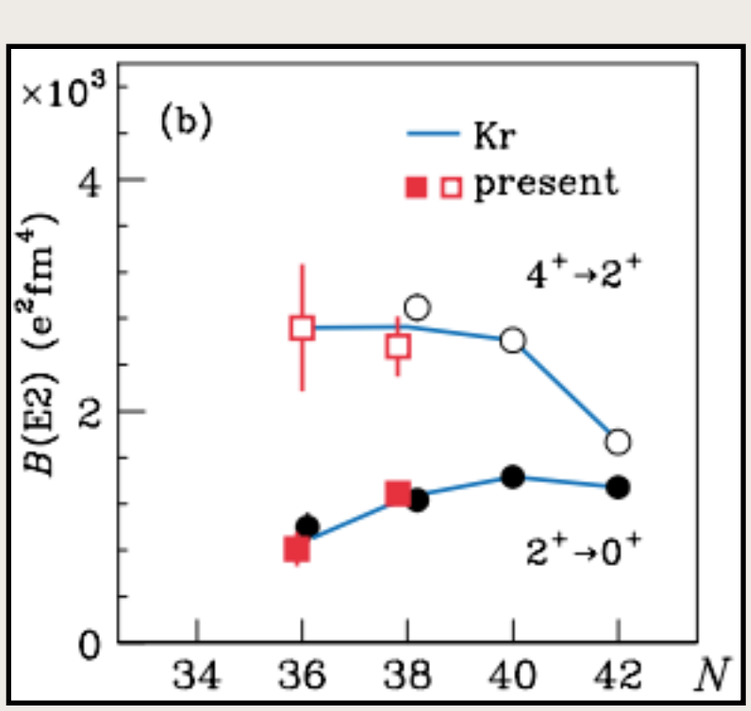
Used a triple plunger - allows for a wide range of lifetimes (1-100ps)

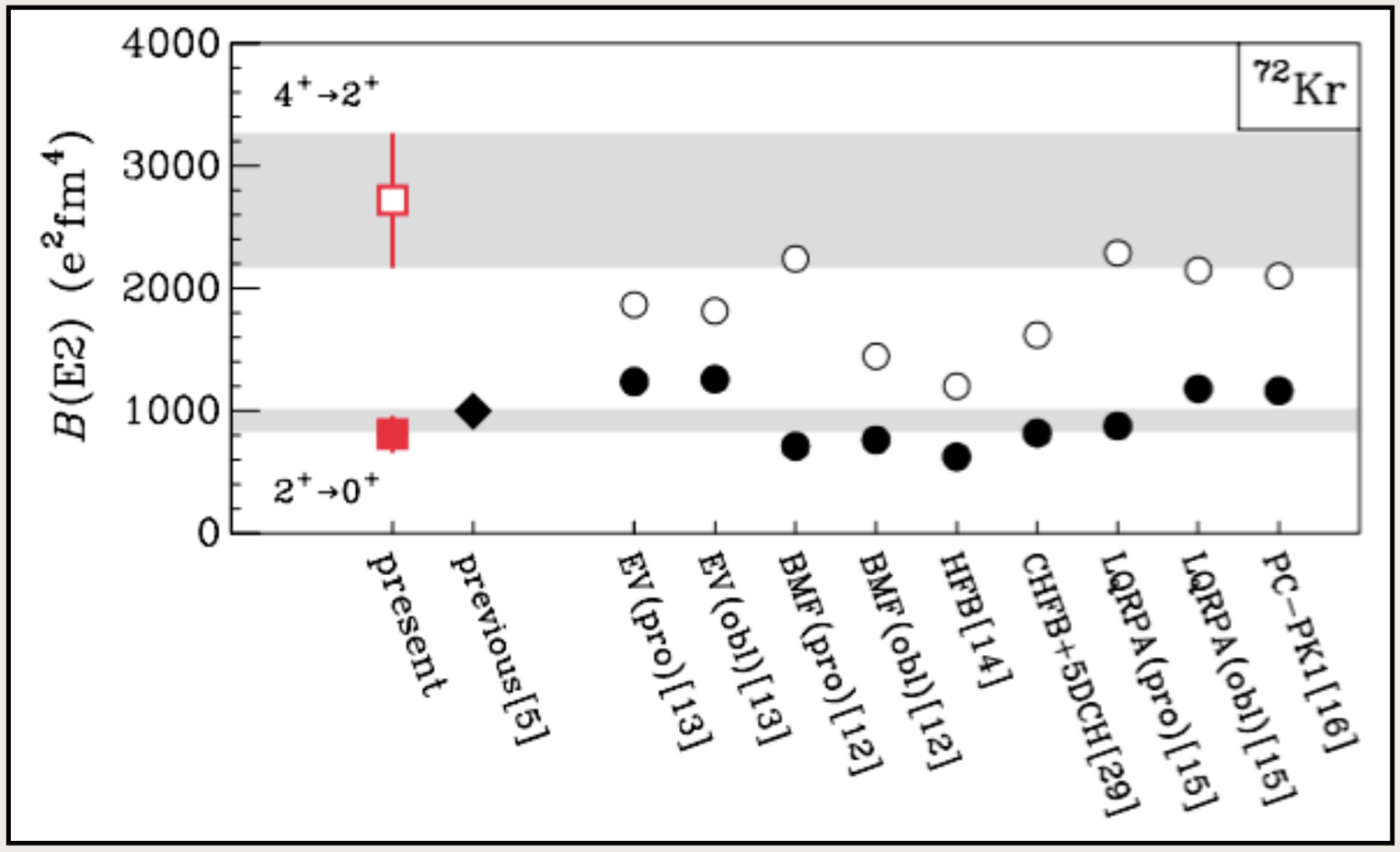
^{74}Kr used as a test case

Recoil-distance Doppler shift

Example, ^{72}Kr:

Models struggle to reproduce vastly different B(E2)s





Could be explained by a change in shape…?

Doppler-shift attenuation method

For yet shorter lifetimes, recoils decay before traversing the medium between foils

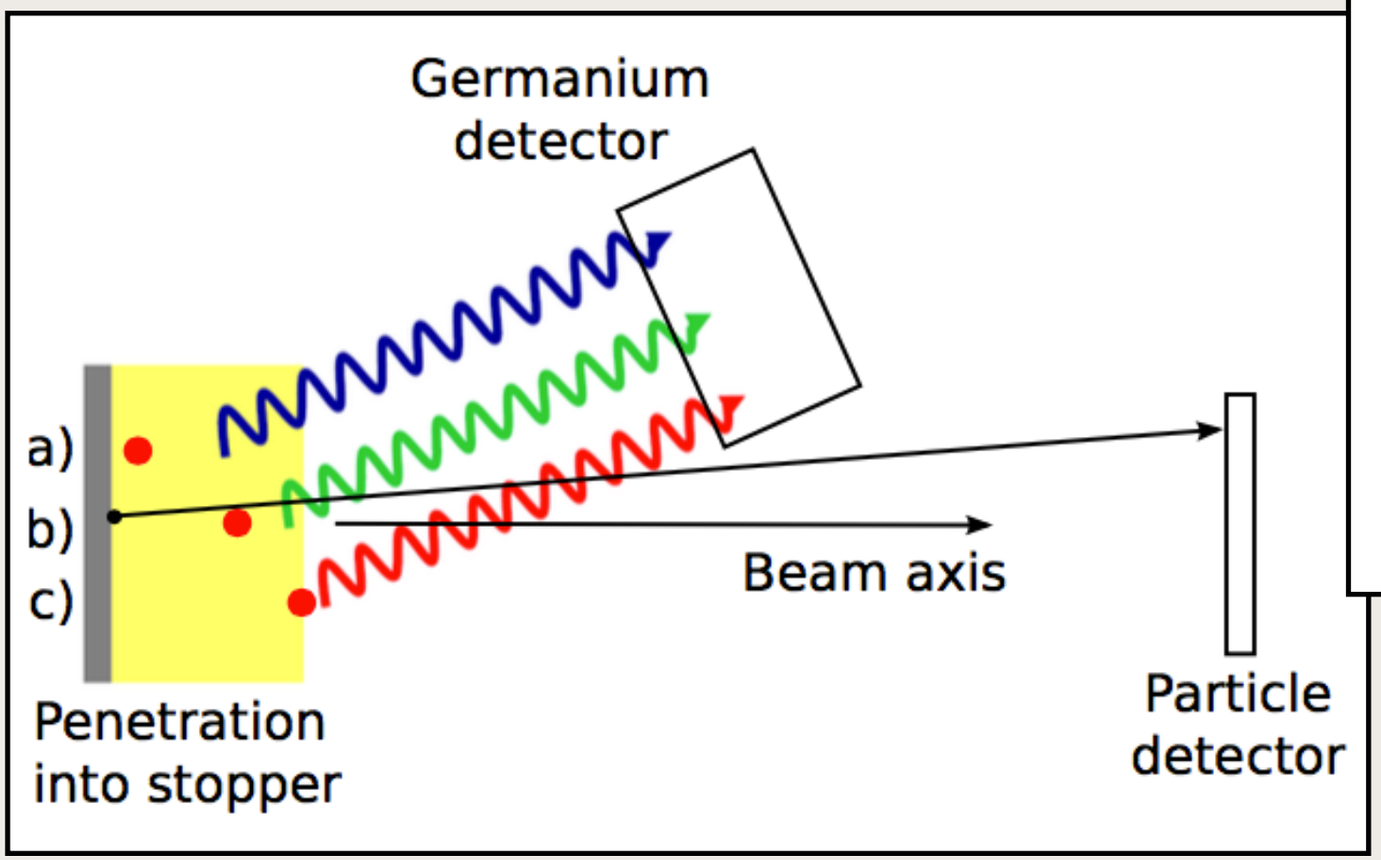
Proceed using the Doppler shift coupled with the stopping power of the target

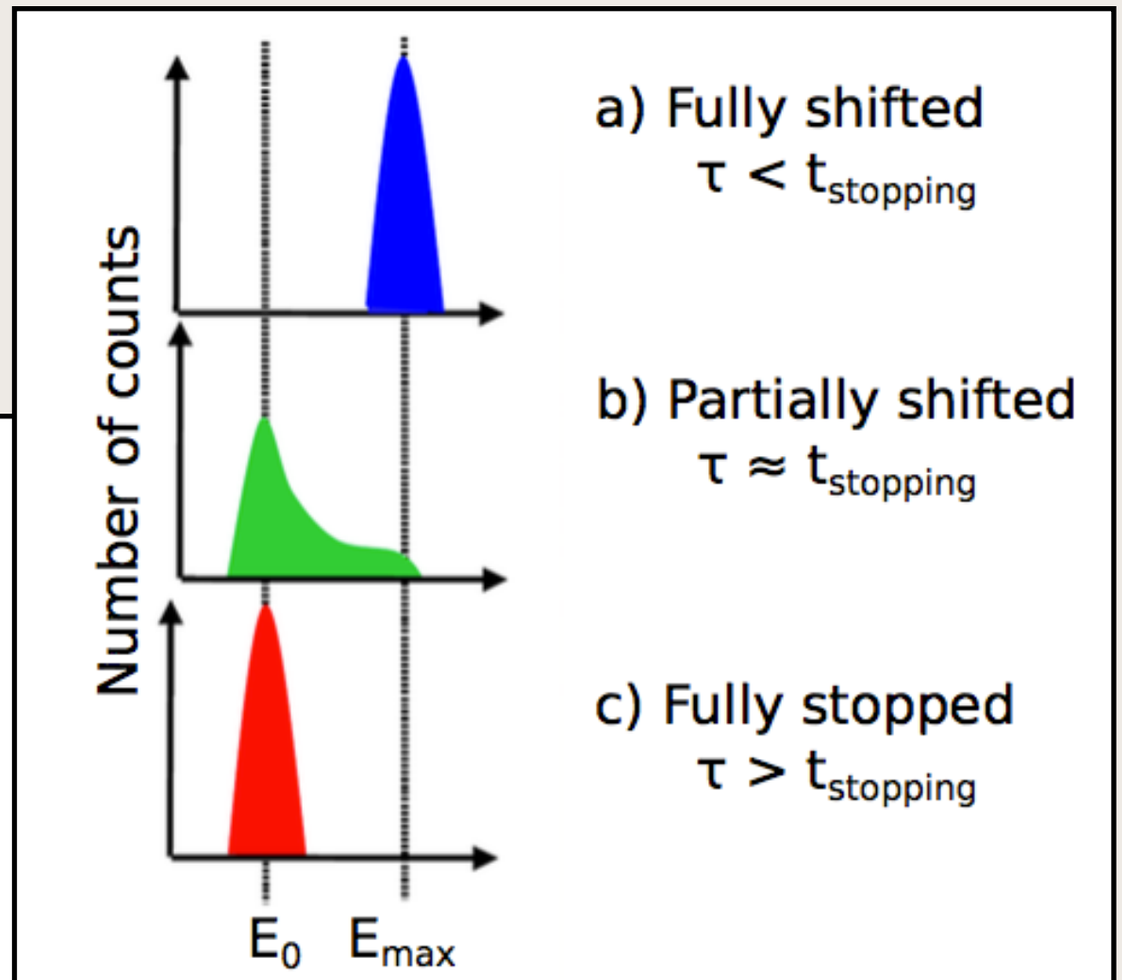
$$E'_\gamma = \frac{E_\gamma}{\gamma \cdot (1 - \beta cos(\theta))}$$

$$F(\tau) = \frac{1}{v_0 \tau} \int_0^\infty v(t) exp\left(-\frac{t}{\tau}\right) dt$$

Doppler-shift attenuation method

Results in a distribution of γ-ray energies



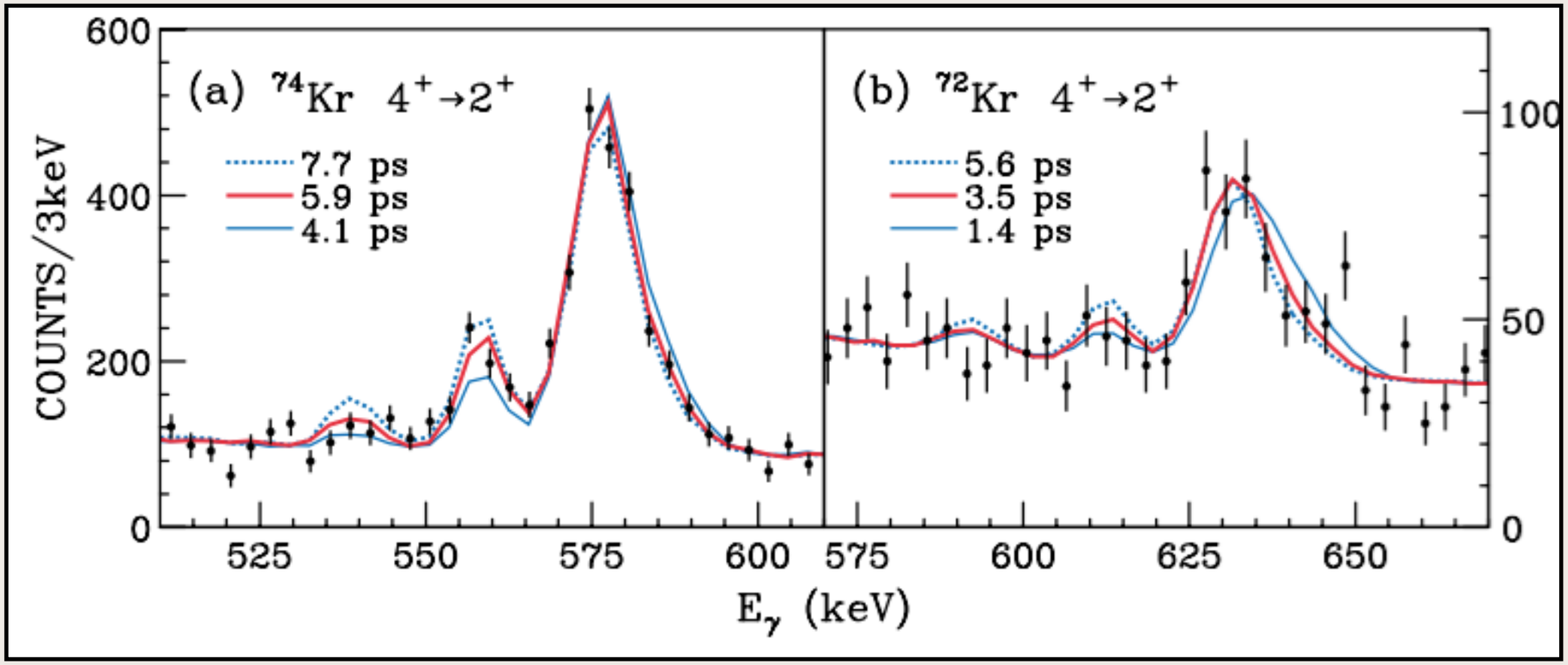


Distribution depends on state lifetimes

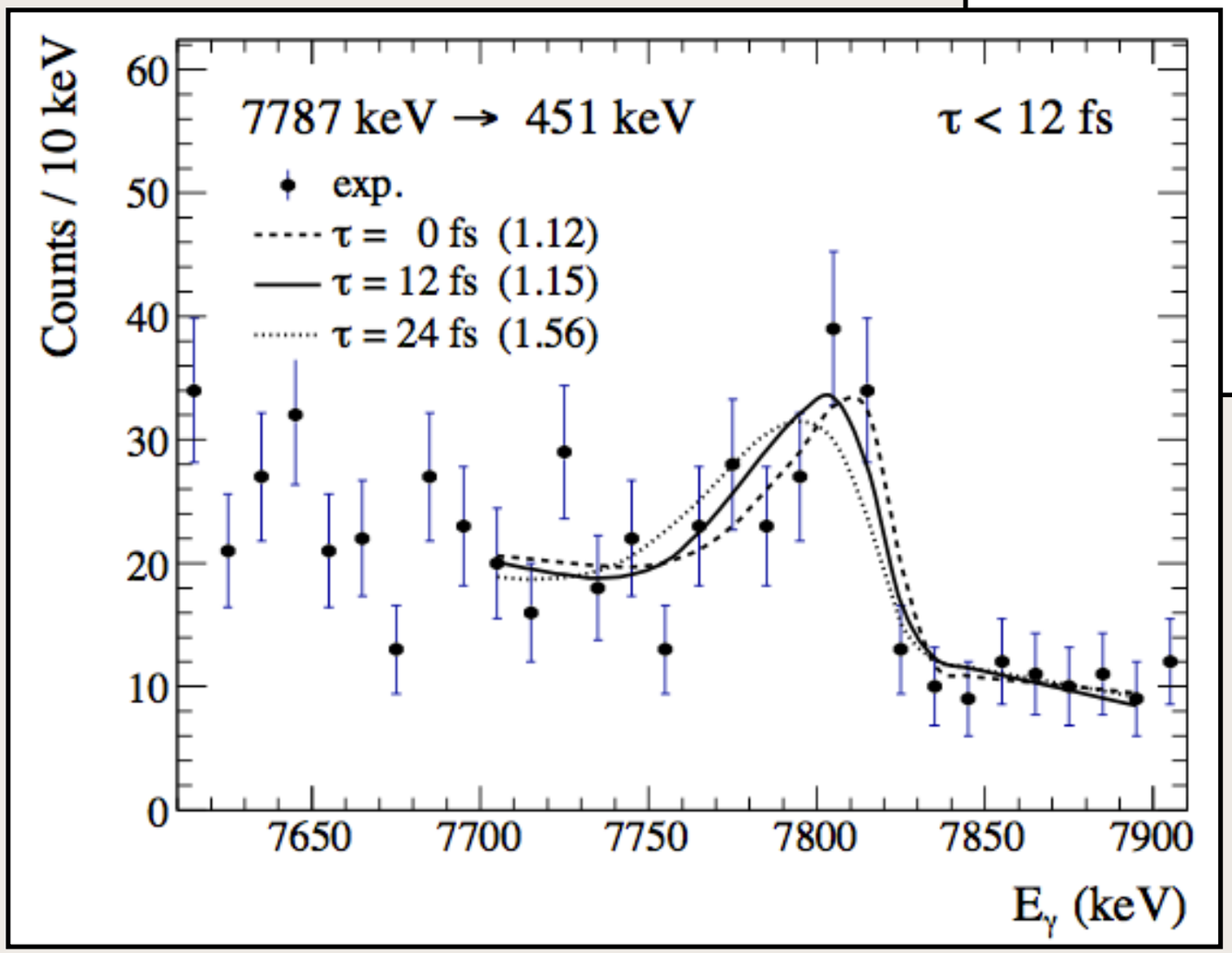
Lineshape methods

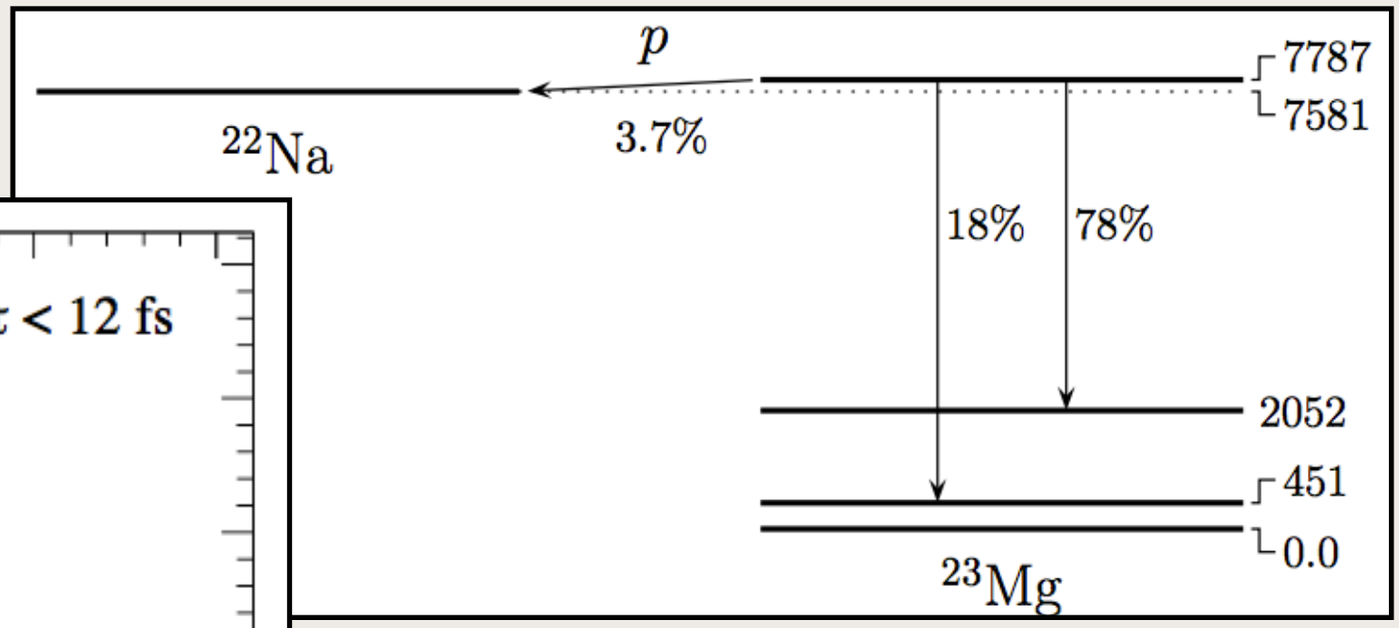
For even shorter lifetimes (~fs) no distinct shape can be resolved

Instead, have to model the line shape of the decay (basically: DSAM but trickier…)



Lineshape methods



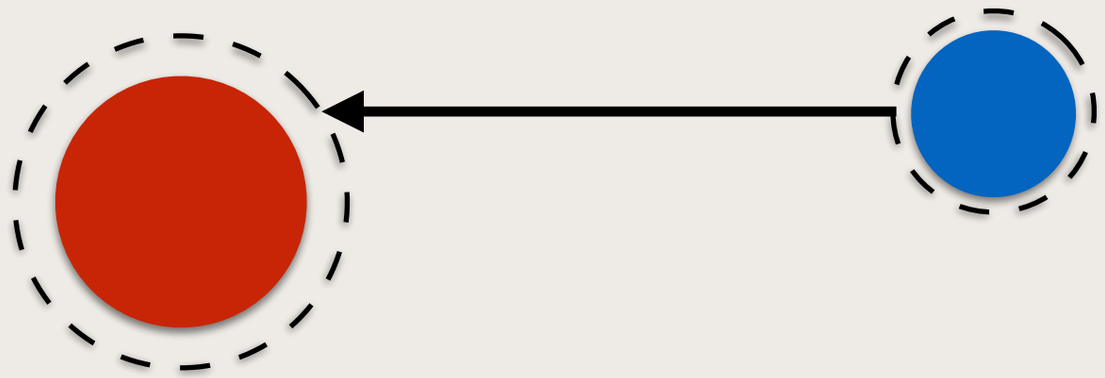


$$\omega\gamma = \frac{2J+1}{(2J_p+1)(2J_{Na}+1)}\frac{\hbar}{\tau}B_p(1-B_p)$$

Inferring lifetimes

In addition to directly measuring the lifetime of the state, some reactions can be used to infer it.

e.g. Coulomb excitation



If we make sure our nuclei don't touch, the nuclear forces don't contribute… can basically just consider electromagnetic effects
…which are entirely understood

Coulomb excitation

Since we are only dealing with an electromagnetic interaction, the entire reaction can be solved

$$\frac{da_k}{d\omega} = -i \sum_{\lambda\mu n} Q_{\lambda\nu}(\epsilon,\omega)\zeta_{kn}^{\lambda\mu} \cdot \langle I_k||M(\lambda)||I_n\rangle \cdot exp(i\zeta_{kn}(\epsilon sinh(\omega)+\omega)) \cdot a_n(\omega)$$

Looks complicated, but is solvable

Importantly, the transition matrix element is directly related to the cross section

“Safe” Coulomb excitation

In order to ensure that there are no nuclear contributions, we define a “safe” Coulomb excitation limit.

Basically, we demand that there is a 5 fm separation between nuclear surfaces

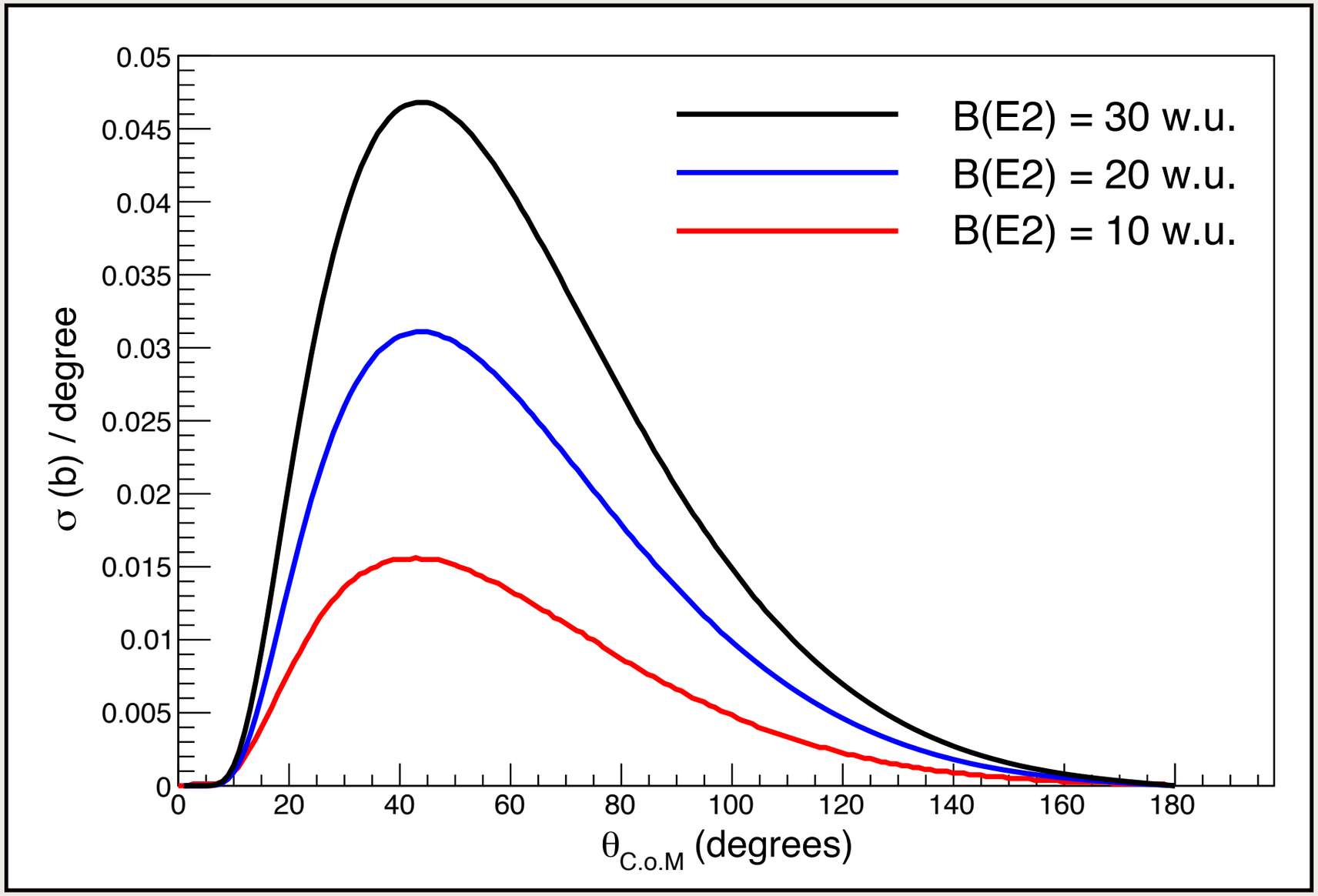
$$E_{max}(MeV) = 1.44 \frac{(A_1 + A_2) \cdot Z_1 Z_2}{A_2} \frac{1}{1.25\left(A_1^{1/3} + A_2^{1/2}\right) + 5}$$

Energy to bring projectile (1) to with a given separation R of target particle (2)

R (separation)

What do we measure?

We measure the cross-section vs scattering angle, which relates directly to the transition matrix elements



Coulomb excitation

An example:

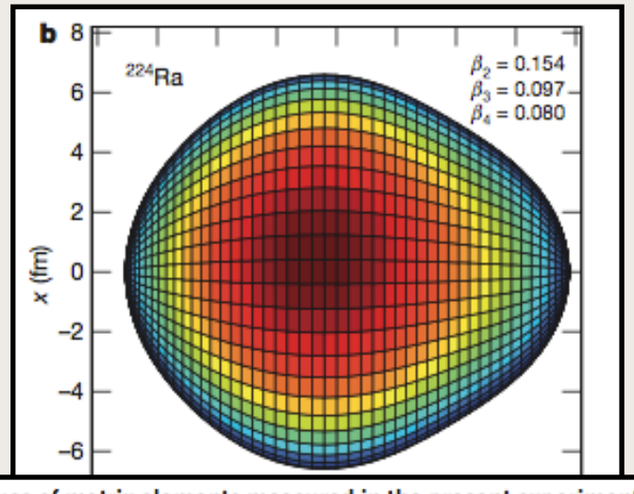
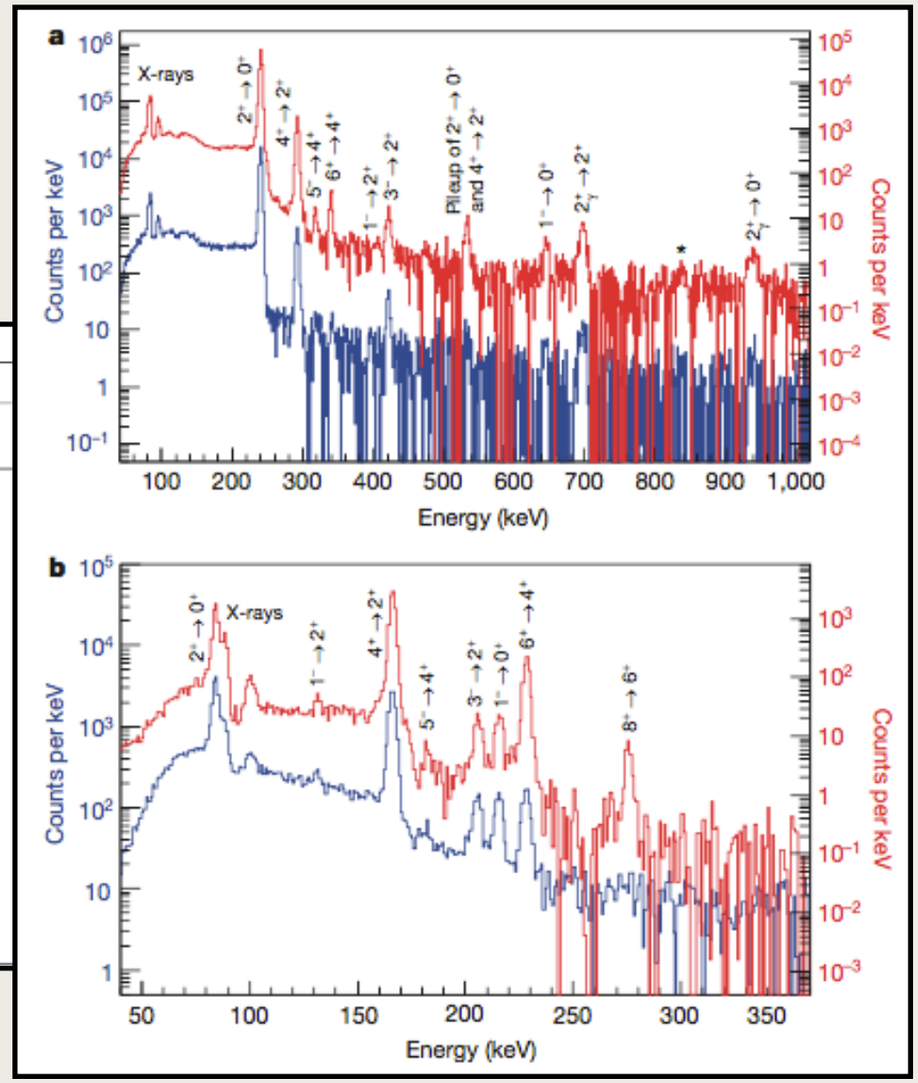


Table 1 | Values of matrix elements measured in the present experiment

Matrix element	^{220}Rn		^{224}Ra	
$\langle I' \| \| E\lambda \| \| I \rangle$	$\lvert$m.e.$\rvert$ ($e\,fm^{\lambda}$)	$B(E\lambda)\downarrow$ (WU)	$\lvert$m.e.$\rvert$ ($e\,fm^{\lambda}$)	$B(E\lambda)\downarrow$ (WU)
$\langle 0^+ \| \| E1 \| \| 1^- \rangle$	<0.10	$<1.5 \times 10^{-3}$	<0.018	$<5 \times 10^{-5}$
$\langle 2^+ \| \| E1 \| \| 1^- \rangle$	<0.13	$<3 \times 10^{-3}$	<0.03	$<1.3 \times 10^{-4}$
$\langle 2^+ \| \| E1 \| \| 3^- \rangle$	<0.18	$<2 \times 10^{-3}$	0.026 ± 0.005	$3.9^{+1.7}_{-1.4} \times 10^{-5}$
$\langle 4^+ \| \| E1 \| \| 5^- \rangle$	0.028 ± 0.009	$3.0^{+2}_{-1.6} \times 10^{-5}$	0.030 ± 0.010	$4^{+3}_{-2} \times 10^{-5}$
$\langle 6^+ \| \| E1 \| \| 7^- \rangle$	<1.3	<0.5	<0.10	$<3 \times 10^{-4}$
$\langle 0^+ \| \| E2 \| \| 2^+ \rangle$	137 ± 4	48 ± 3	199 ± 3	98 ± 3
$\langle 1^- \| \| E2 \| \| 3^- \rangle$	180 ± 60	60^{+50}_{-30}	230 ± 11	93 ± 9
$\langle 2^+ \| \| E2 \| \| 4^+ \rangle$	212 ± 4	63 ± 3	315 ± 6	137 ± 5
$\langle 3^- \| \| E2 \| \| 5^- \rangle$	220 ± 150	60^{+100}_{-50}	410 ± 60	190 ± 60
$\langle 4^+ \| \| E2 \| \| 6^+ \rangle$	274 ± 14	73 ± 8	405 ± 15	156 ± 12
$\langle 6^+ \| \| E2 \| \| 8^+ \rangle$			500 ± 60	180 ± 60
$\langle 0^+ \| \| E2 \| \| 2^+_\gamma \rangle$	32 ± 7	2.6 ± 1.1	23 ± 4	1.3 ± 0.5
$\langle 0^+ \| \| E3 \| \| 3^- \rangle$	810 ± 50	33 ± 4	940 ± 30	42 ± 3
$\langle 2^+ \| \| E3 \| \| 1^- \rangle$	<2,600	<760	$1,370 \pm 140$	210 ± 40
$\langle 2^+ \| \| E3 \| \| 3^- \rangle$	<5,300	<1,400	<4,000	<600
$\langle 2^+ \| \| E3 \| \| 5^- \rangle$	$1,700 \pm 400$	90 ± 50	$1,410 \pm 190$	61 ± 17



Octupole deformation in radon and radium

Summary

- State lifetimes are a vital experimental observables
- Relate to reduced matrix elements - B(λL)
- Vital input for many nuclear models
  - Large B(E2)s indicate collectivity
  - Can be used to probe shell closures
- A number of experimental techniques - covering most potential lifetimes